Indirect Searches for Dark Matter

James Buckley

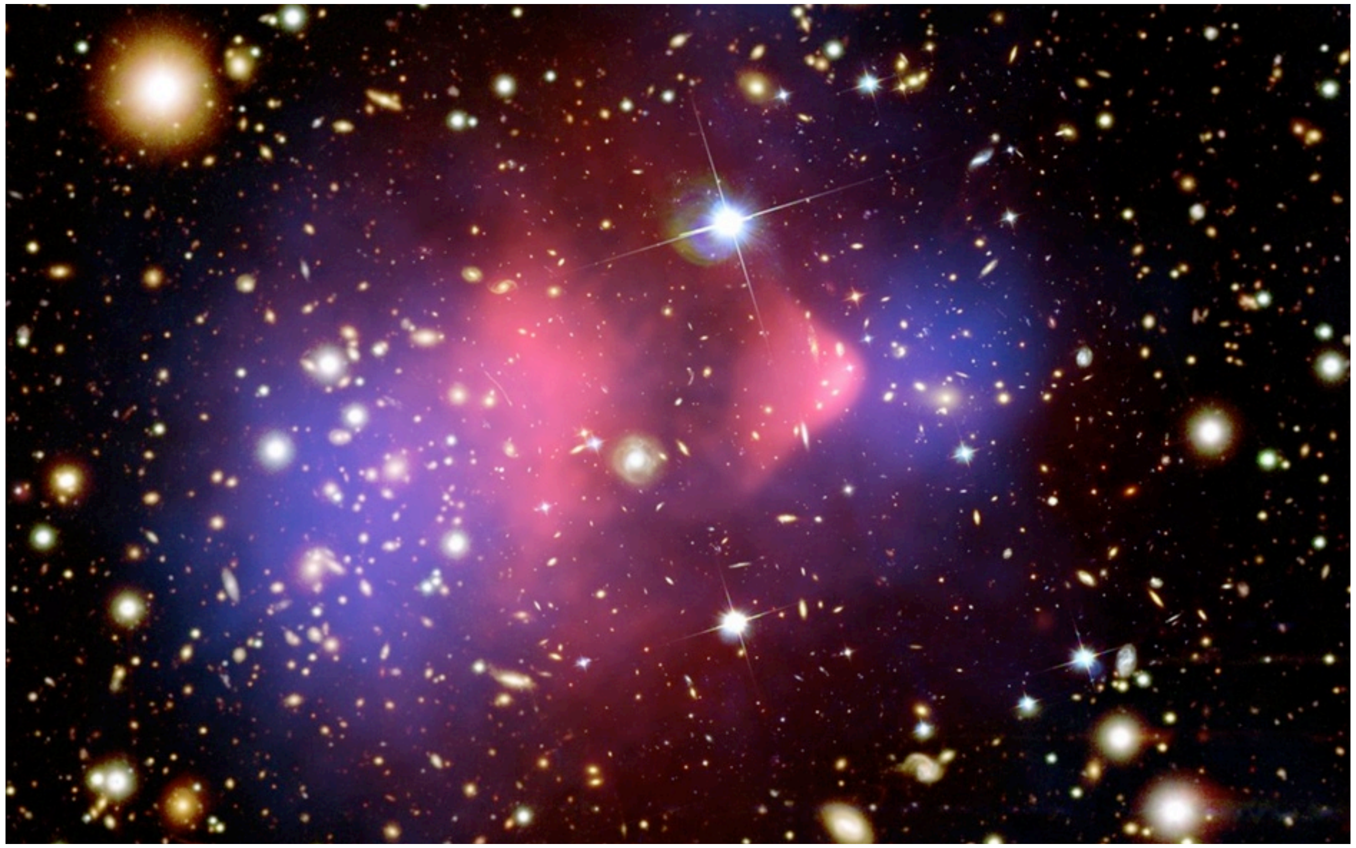
Washington University, St. Louis

Thanks to VERITAS collaboration, CTA consortium, Slava Bugaev, Francesc Ferrer, Matthieu Vivier and creators of DARKSUSY, Gondolo, Edsjo, Bergstrom, Ullio, Schelke, Baltz, Bringmann and Duda)

- Indirect Dark Matter Searches: electrons, neutrinos and gammas
- Future experiments
- Complimentarity

Midwest Dark Matter Mini Workshop FNAL April 6, 2012

Dark Matter Intro



Gravitational effect of DM is visible in many astrophysical settings.

Bullet cluster image shows gravitational mass inferred from lensing (blue) and X-ray emission from baryonic matter (red).

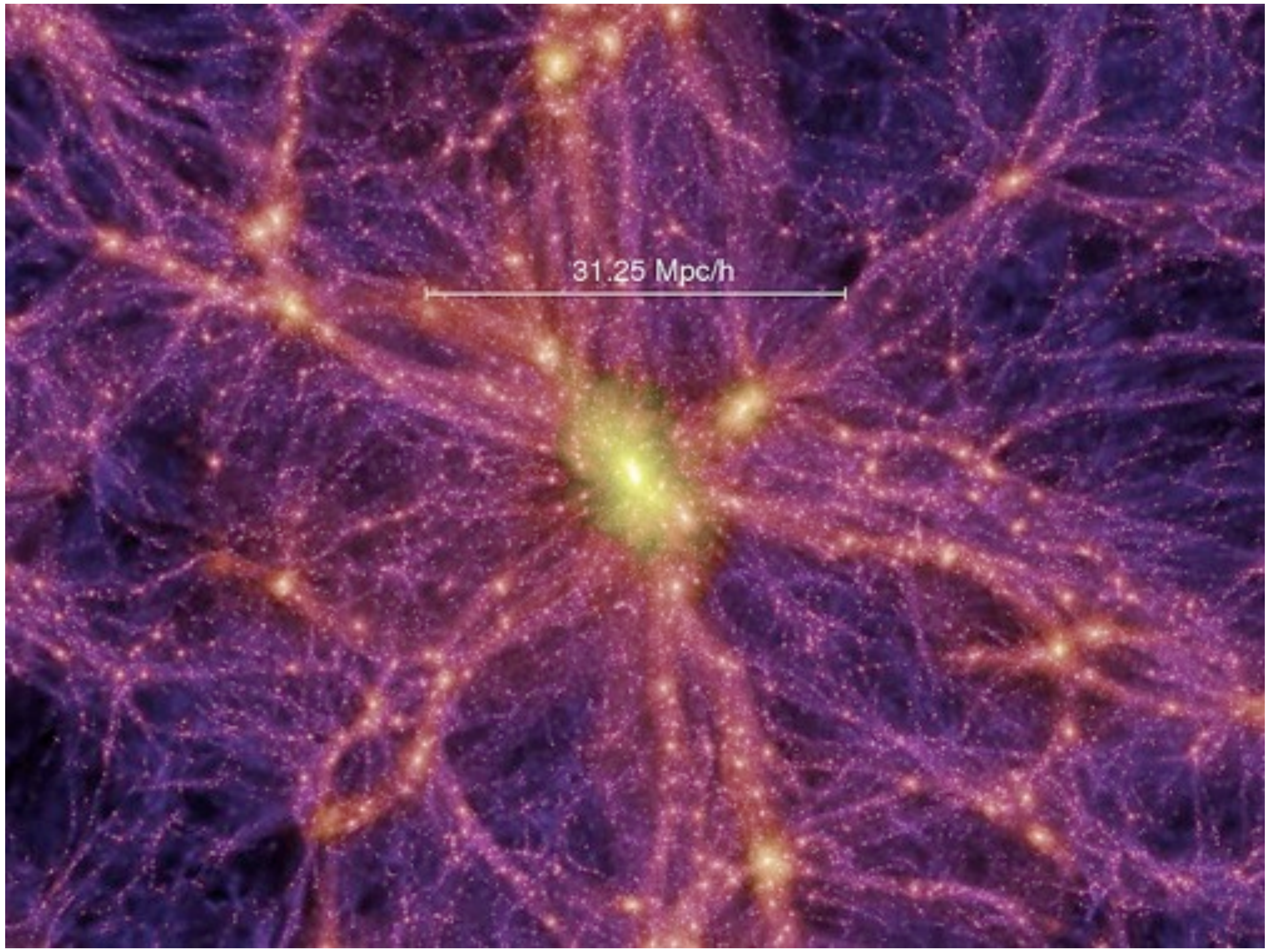
Not modified gravity, not gas - dark matter behaves like stars, weakly interacting particles

$$\text{From WMAP}: \ \Omega_{\rm DM} h^2 = 0.1123 \pm 0.0035$$

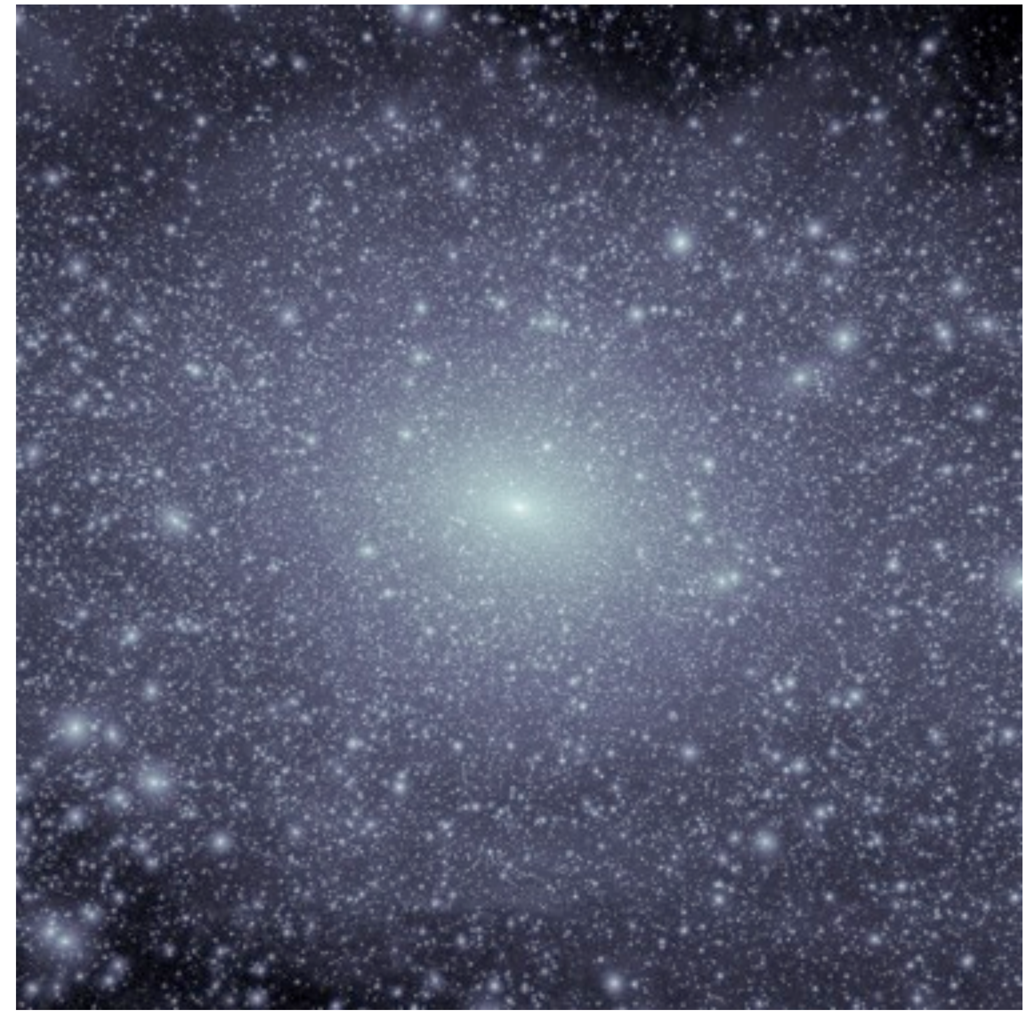
For a thermal relic of the big bang, the larger the annihilation cross section the longer the DM stays in equilibrium and the larger the Boltzmann suppression $\sim e^{-m_\chi/kT}$ before freeze-out.

$$\Omega_\chi \approx \frac{0.1}{h^2}\left(\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{sec}^{-1}}{\langle\sigma v\rangle}\right)$$

Dark Matter Halos



(Millenium simulation)



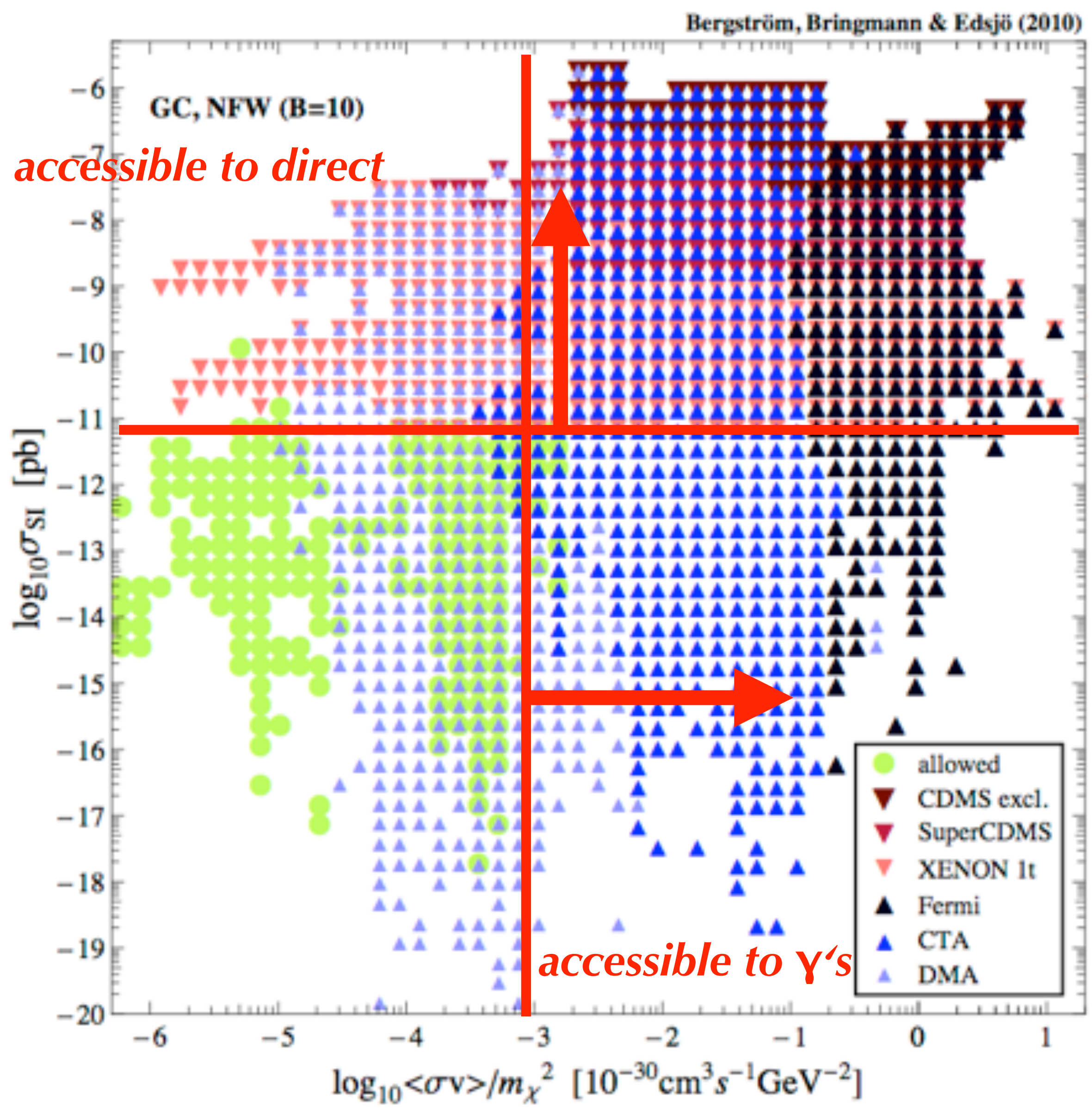
(VL Lactea II Simulation)

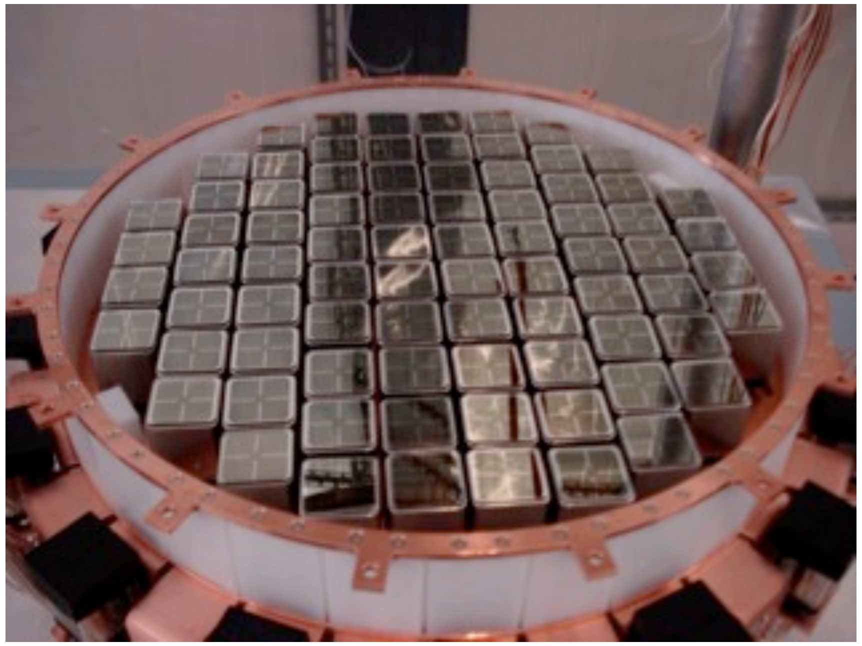
- Cold dark matter also required for structure formation. In regions of highest density, WIMPS (e.g., neutralinos) annihilate forming standard model particles and photons

Direct and Indirect Detection

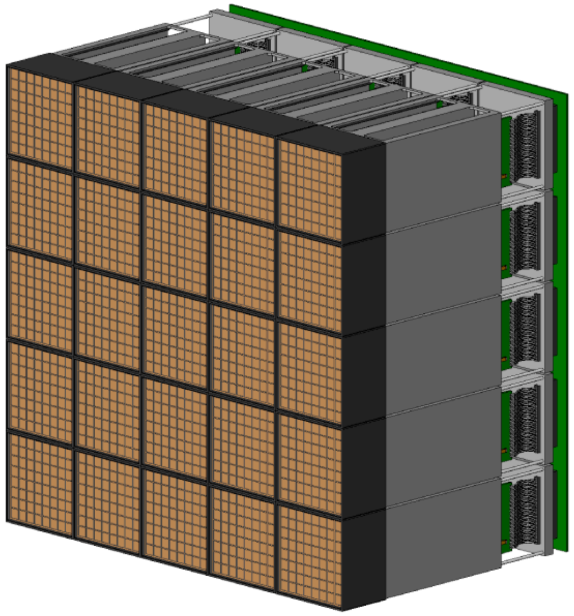
Dark Matter can be directly detected through nuclear recoil in "direct detection" experiments, missing energy or momentum in accelerators, or through detection of products of annihilation in astrophysical halos

[hep-ph] arXiv:1011.4514 L. Bergstrom et al.



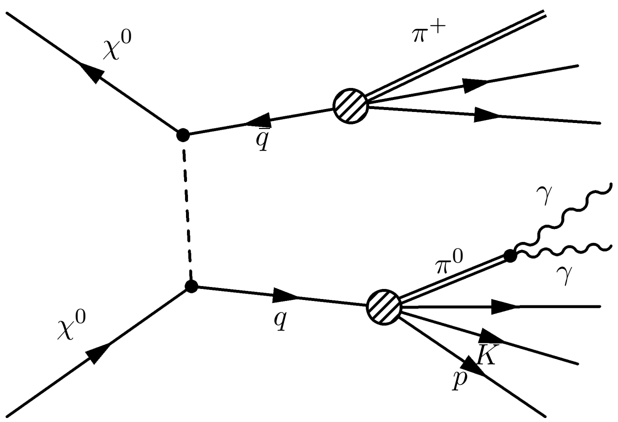


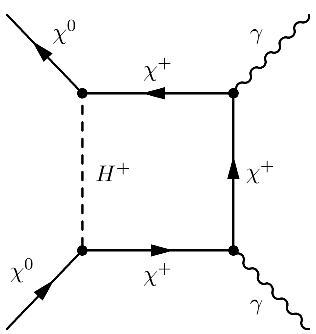
Xenon100

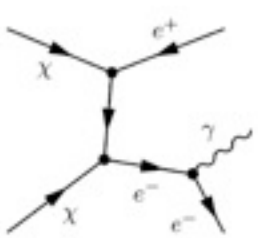


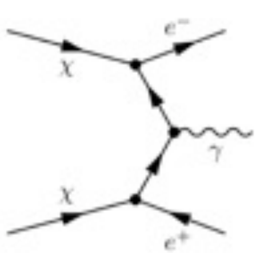
Proposed CTA SC camera module

Annihilation Channels









Annihilation Channel	Secondary Processes	Signals	Notes
$\chi\chi \to q\bar{q},\ gg$	$p, \bar{p}, \pi^{\pm}, \pi^0$	p, e, ν, γ	
$\chi\chi \to W^+W^-$	$W^{\pm} \to l^{\pm}\nu_l,\ W^{\pm} \to u\bar{d} \to \pi^{\pm},\ \pi^0$	p, e, ν, γ	
$\chi\chi \to Z^0Z^0$	$Z^0 \to l\bar{l},\ \nu\bar{\nu},\ q\bar{q} \to$ pions	p, e, γ, ν	
$\chi\chi \to \tau^{\pm}$	$\tau^{\pm} \to \nu_\tau e^{\pm}\nu_e,\ \tau \to \nu_\tau W^{\pm} \to p, \bar{p}$, pions	p, e, γ, ν	
$\chi\chi \to \mu^+\mu^-$		e, γ	Rapid energy loss of μs in sun before decay results in sub-threshold νs
$\chi\chi \to \gamma\gamma$ $\chi\chi \to Z^0\gamma$	Z^0 decay	γ γ	Loop suppressed Loop suppressed
$\chi\chi \to e^+e^-$		e, γ	Helicity suppressed
$\chi\chi \to \nu\bar{\nu}$		ν	Helicity suppressed (important for non-Majorana WIMPs?)
$\chi\chi \to \phi\bar{\phi}$	$\phi \to e^+e^-$	$e^{\pm}$	New scalar field with $m_\chi < m_q$ to explain large electron signal and avoid overproduction of p, γ

internal/final state bremms
inverse Compton γ's

Electron and Antiproton Experiments

Electron Experiments

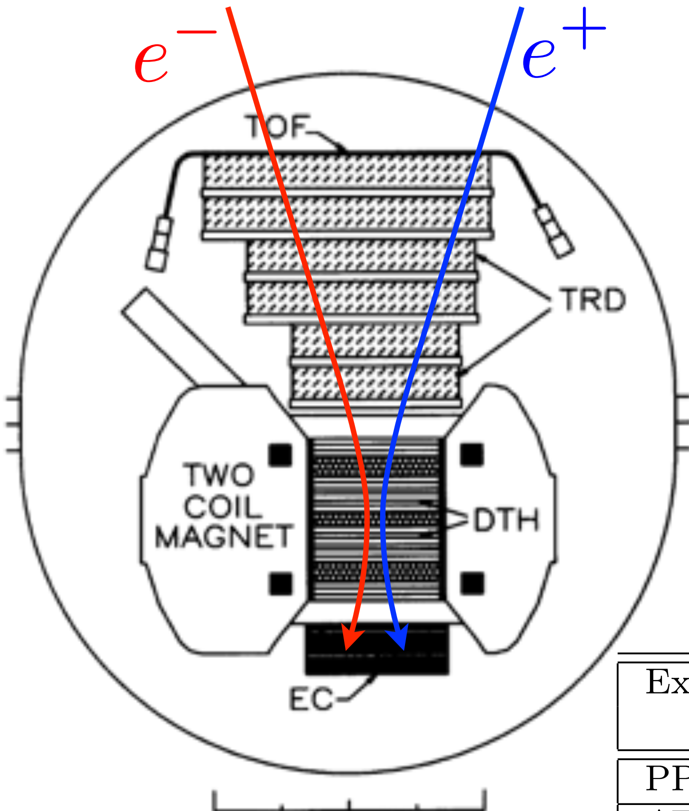
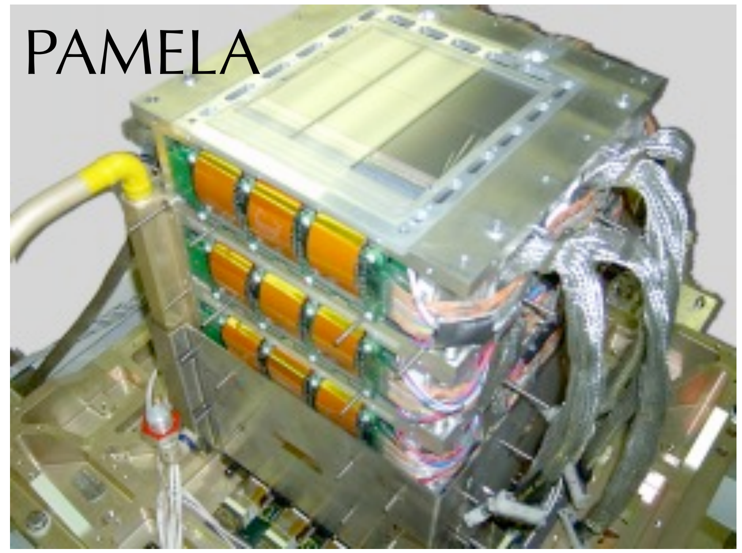
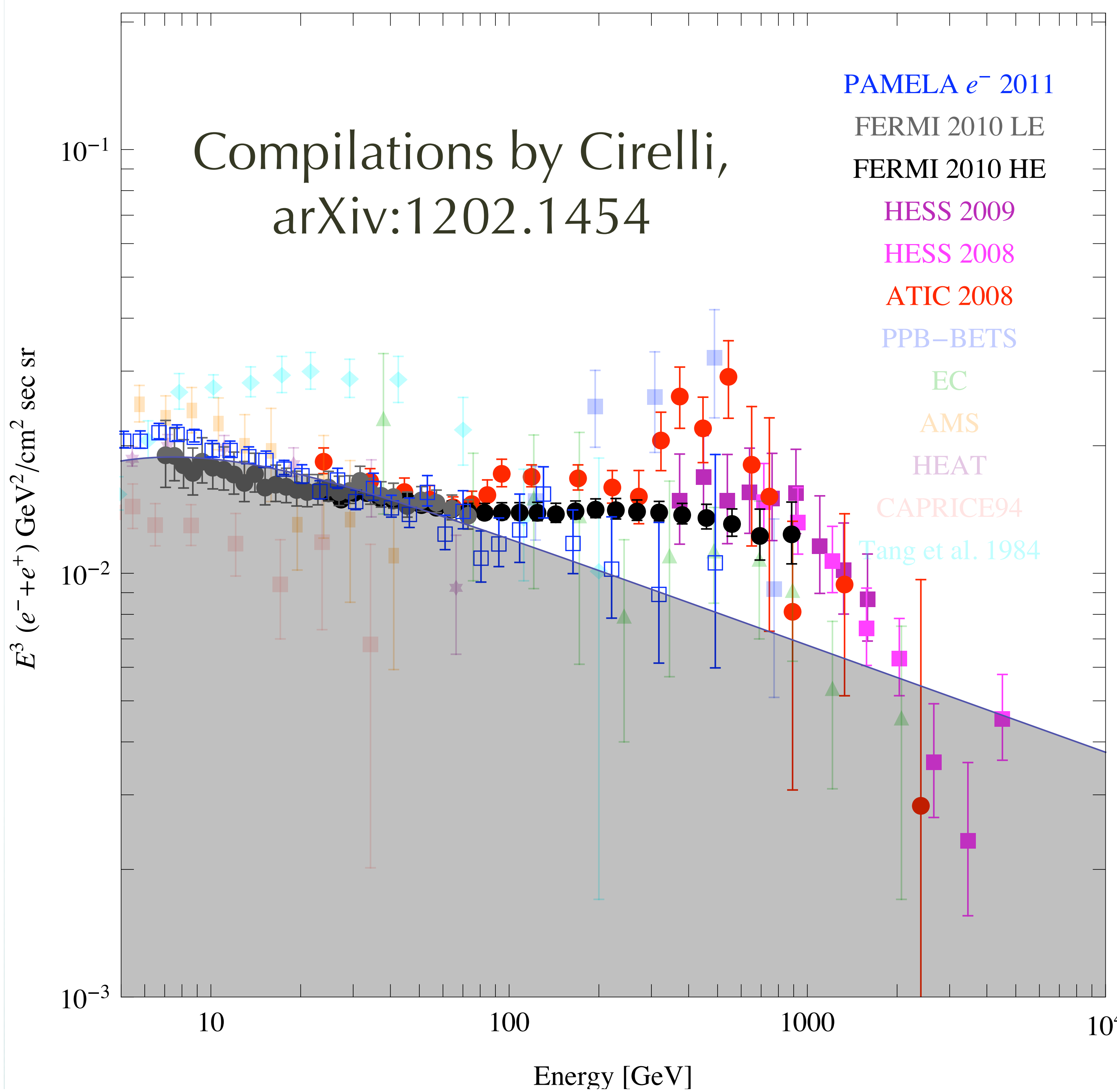


FIG. 2.—HEAT instrument schematic cross section

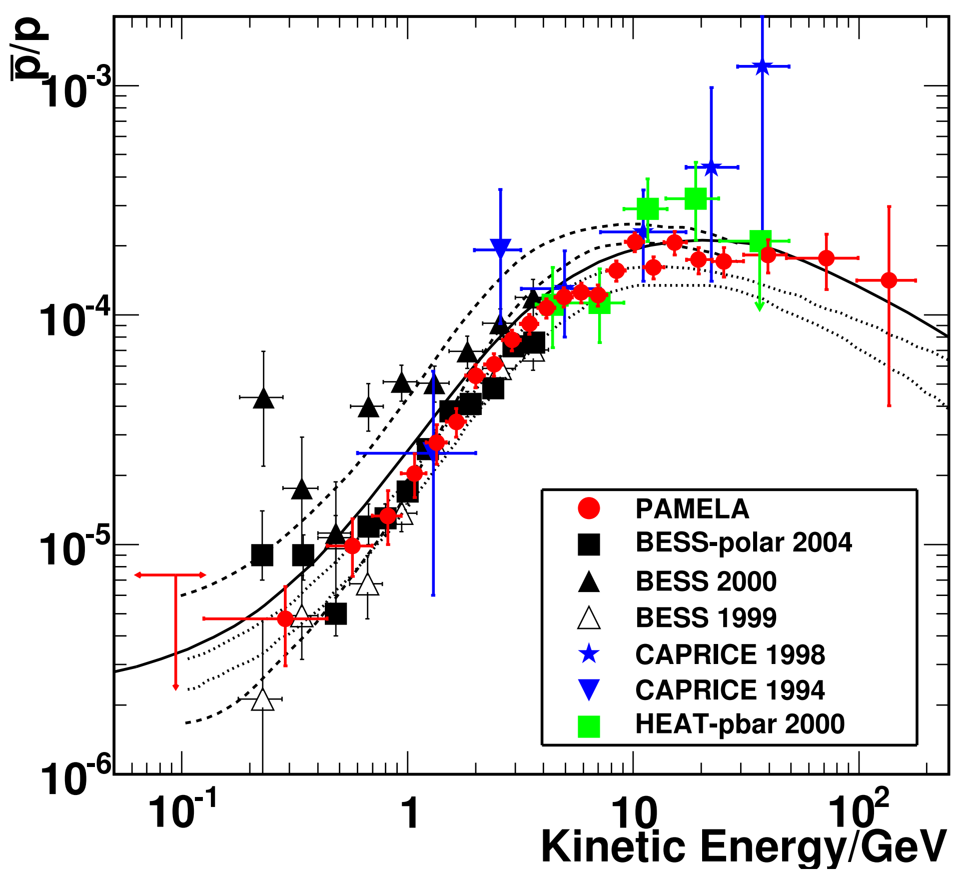


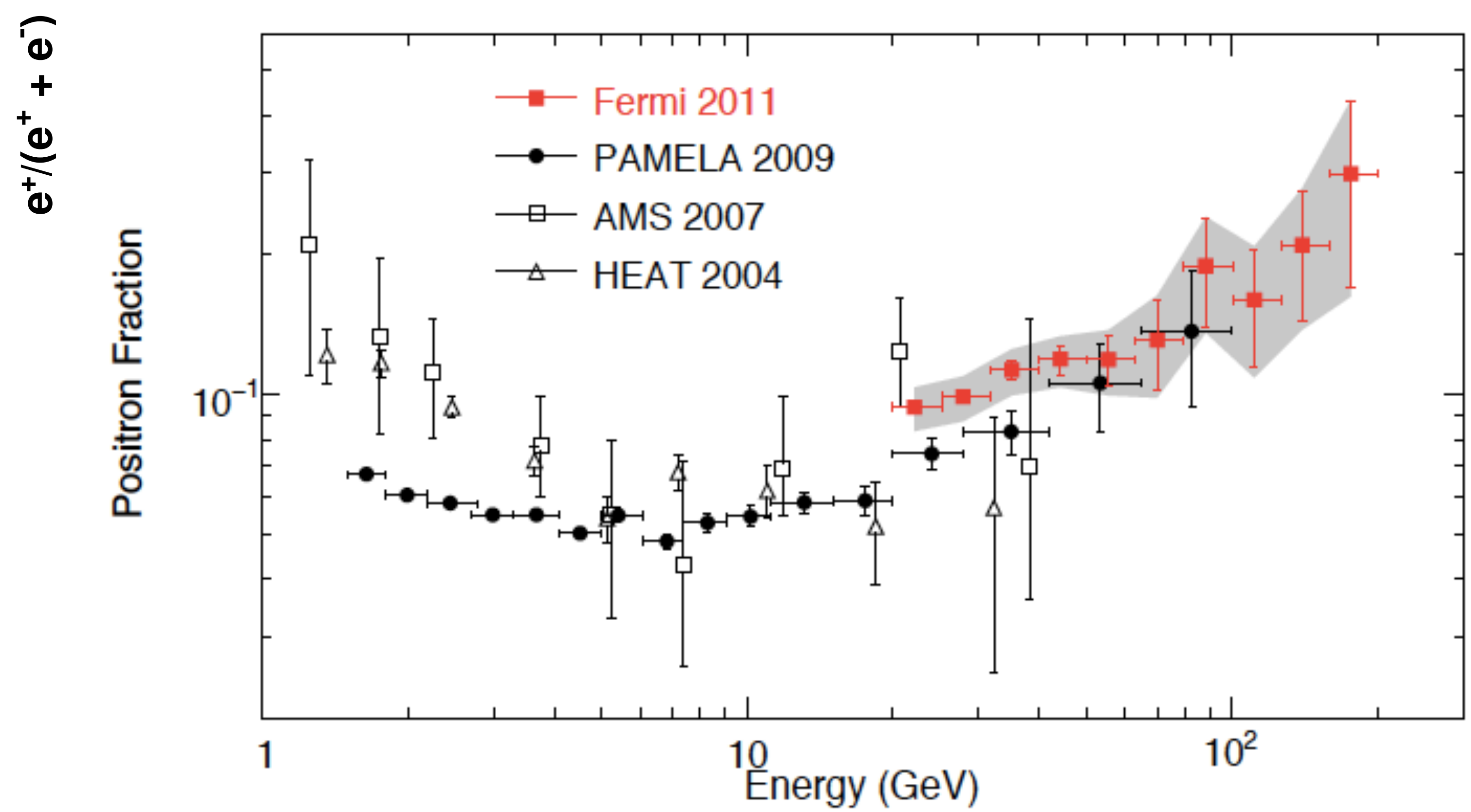
Experiment	Detectors	E Range (GeV)	Exposure ($\mathrm{m^2 sr\,s}$)	Calorimeter Material	Calorimeter Depth	Calorimeter Layers	Magnet Spectrometer B_{ave}	Magnet Spectrometer σ_x	Magnet Spectrometer length
PPB-BETs	EC	10-800	$\sim 4 \times 10^4$	Pb/SF?	9 X_0	36	N/A		
ATIC	EC	10-100,000	$\sim 3 \times 10^5$	BGO	18 X_0		N/A		
HESS	EC	6-8000 300-800	$\sim 8 \times 10^7$ $\sim 2 \times 10^7$	Air	27 X_0	∞	N/A		
Fermi LAT	EC	20-1000	$\sim 3{\times}10^7$ (181 days)	CsI(Tl)	8.6 X_0		Earth's Field		
PAMELA	EC, MS	50-300 (e^+) 10-700 (e^-)	$\sim$ 1.5 $\times$ 10^5 (850 days) $\sim$ 2.1 $\times$ 10^5 (1200 days)	W/Si	16 X_0	22	0.4 T	$\sim$ 7 μm	40.5 cm/ 6 layers
HEAT	EC, MS, TRD	5-50	$\sim 1.3 \times 10^3$	Pb/PS	9 X_0	10	1 T	70 μm	61 cm/18 layers
Future Experiments									
AMS	EC, MS, TRD, RICH		$\sim 4.5 \times 10^7$ (5 yr)	Pb/SF		18	0.125 T	10 μm	/8 layers
CALET	EC	10-10,000	$\sim$ 2 $\times$ 10^7 (5 yr)	$PbWO_4$	27 X_0		N/A		
VERITAS	EC,MS	100-10,000	$\sim 10^7$	Air	27 X_0	∞	Moon Shadow		

Cosmic-Ray Electrons



Positrons and Antiprotons

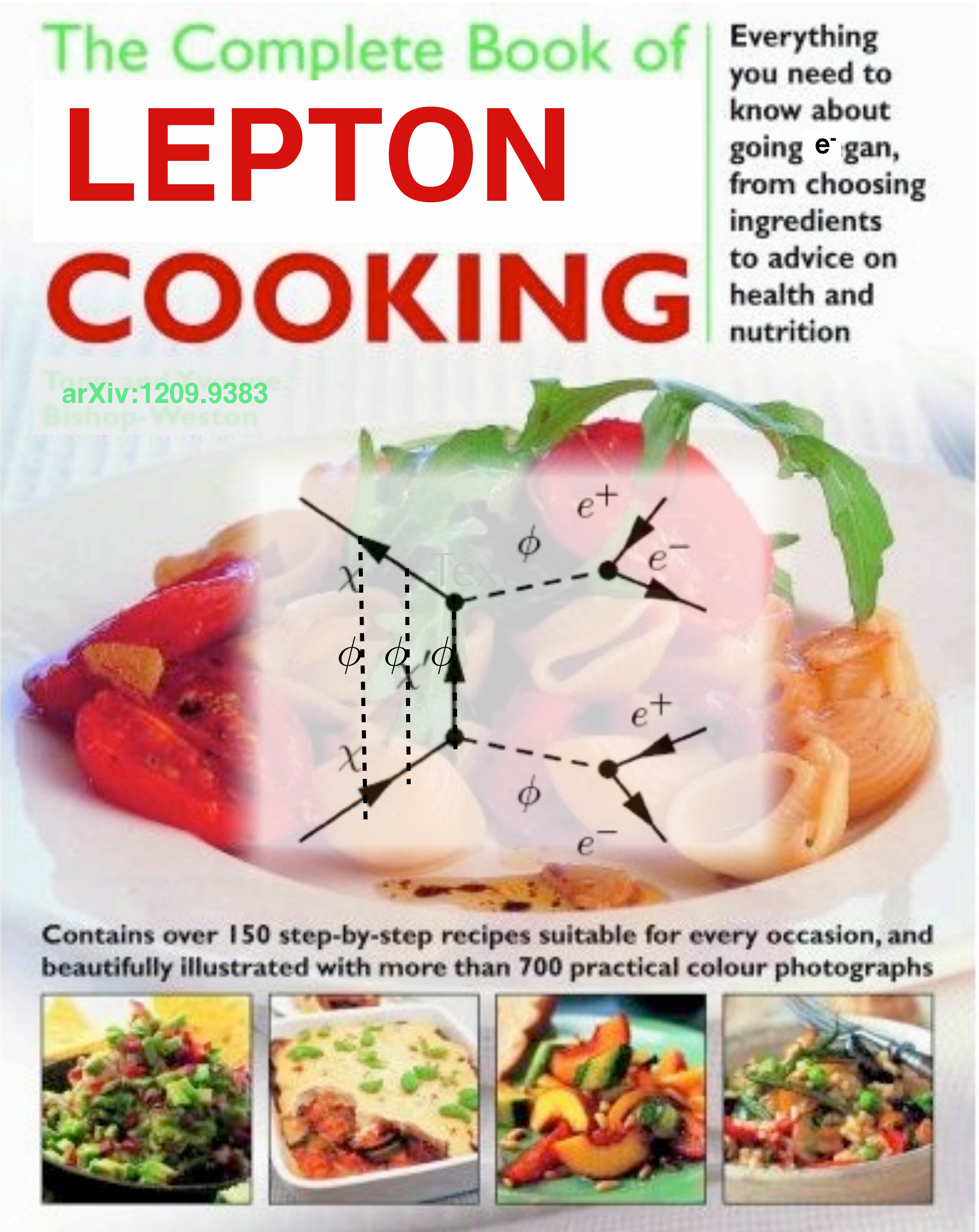




(S. Funk for Fermi-LAT, APS 2012)

- Compared with expected secondary production from cosmic-rays, PAMELA (Fermi) see positron excess but no antiproton excess.
- Leptophillic models to boost electron production, while suppressing hadronic channels.
- These typically require astrophysical or particle physics boosts, electrons produce IC photons - these models can already be constrained by gamma-ray measurements.

Leptonic Models



Chilled Pair Soup

- Start with a standard-model broth mix (see Page 321)
- Add 2 tbs MSugra to sweeten, or season to taste to bring out the more complex flavors.
- Add a dash of scalar fields (be careful not to over-season, make sure the mass is too small to produce an unpleasant hadronic flavor)
- Preheat the oven to 12,000 trillion degrees
- Put in very large pan and heat uncovered for a femtosecond, allowing to gradually cool off. Chill mix and stir vigorously.
- Best if served cold (3 deg K), in a deep bowl with sour cream and dusted with dill.

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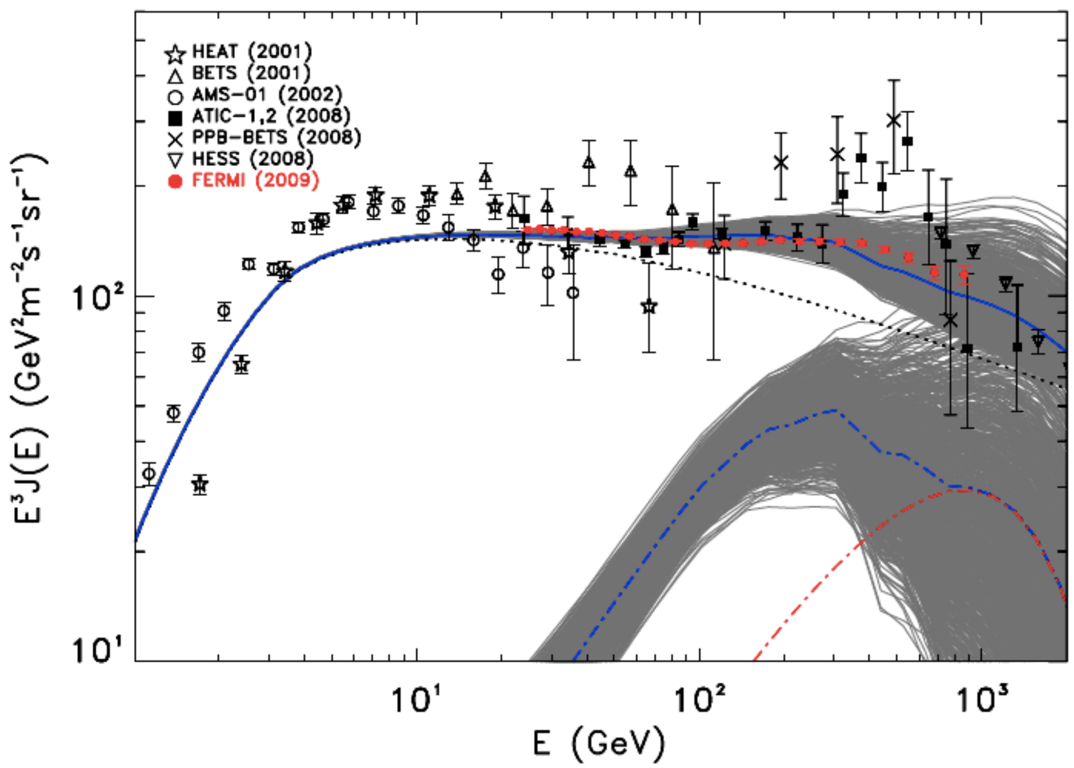
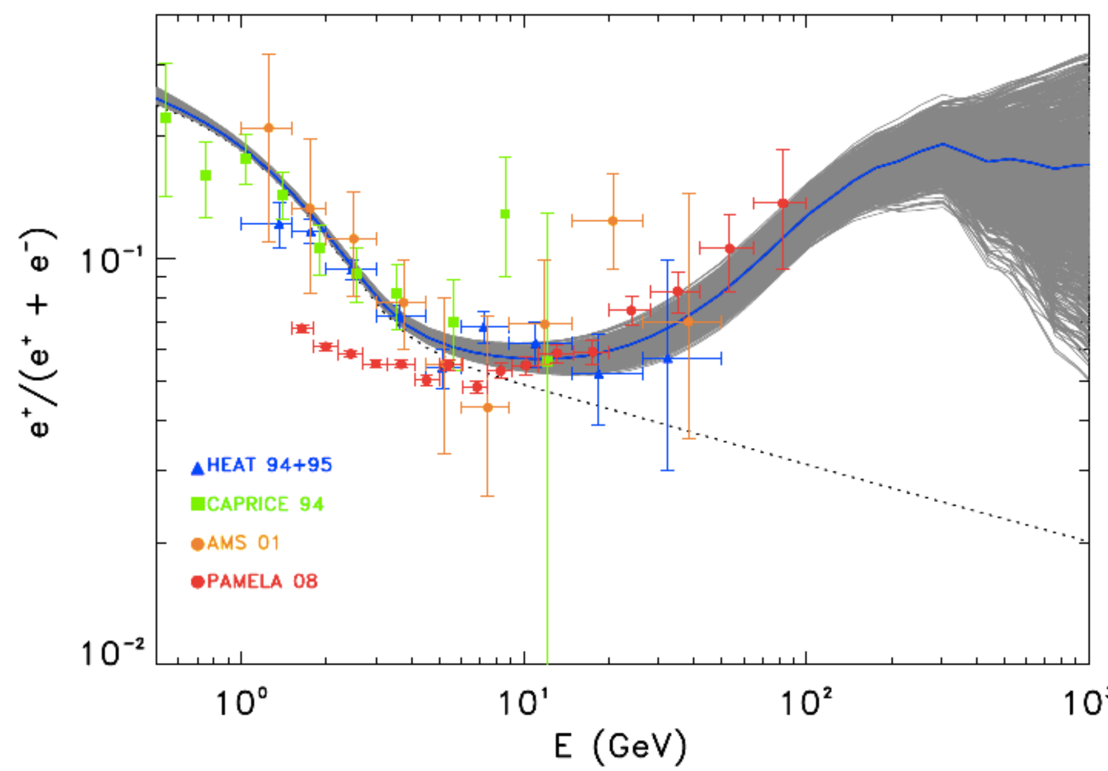
Electrons from Pulsars

Main Contributors to local e+e-:

Nearby (d < 1 kpc) and **Mature** ($10^4 < T/yr < 10^6$) Pulsars





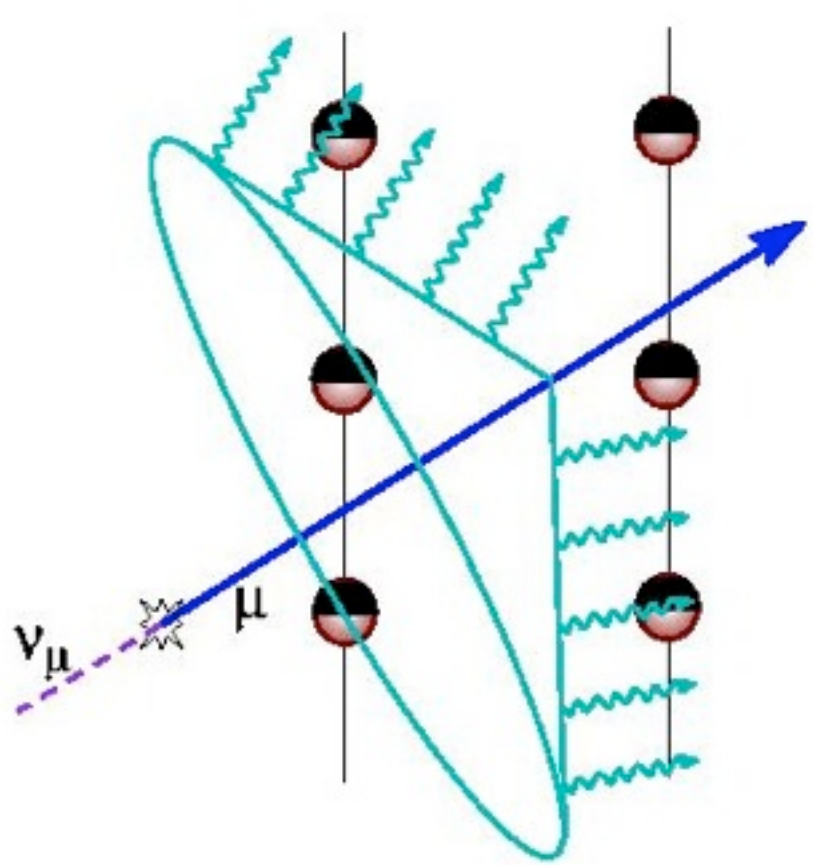
Under reasonable assumptions, electron/positron **emission** from radio **pulsars** (**ATNF** catalogue) offers a **viable interpretation** of **Fermi** CRE data which is also **consistent** with the **HESS** and **Pamela** results

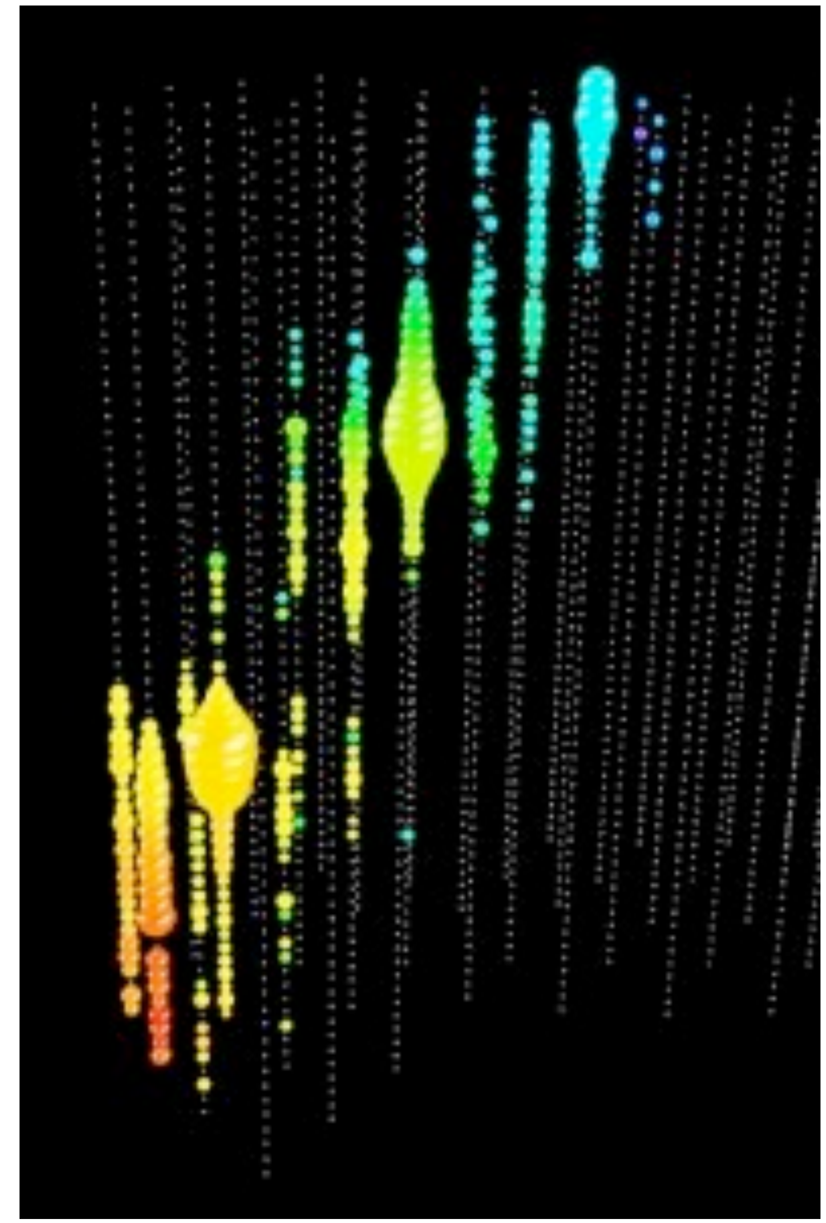
Grasso, Profumo, Strong et al (Fermi Collaboration), 2009

(From S. Profumo, APS, 2012)

Neutrino Experiments

Neutrino Detection





Neutrinos from DM annihilation in the Sun or Galactic Halo travel through Earth, convert to upward going muons which produce Cherenkov light and relatively straight upward going tracks in the PMTs

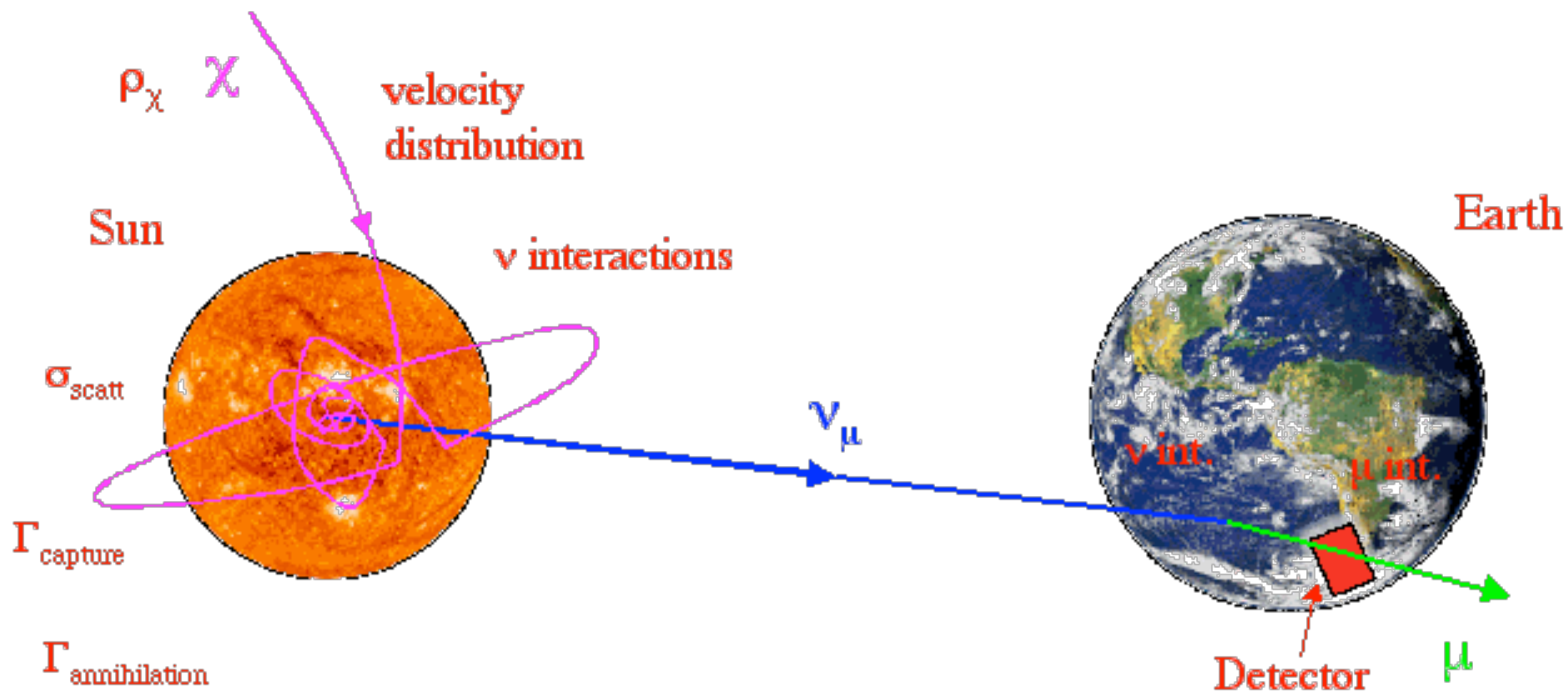
(simulated neutrino event in ICECUBE)

Neutrino Capture by Sun

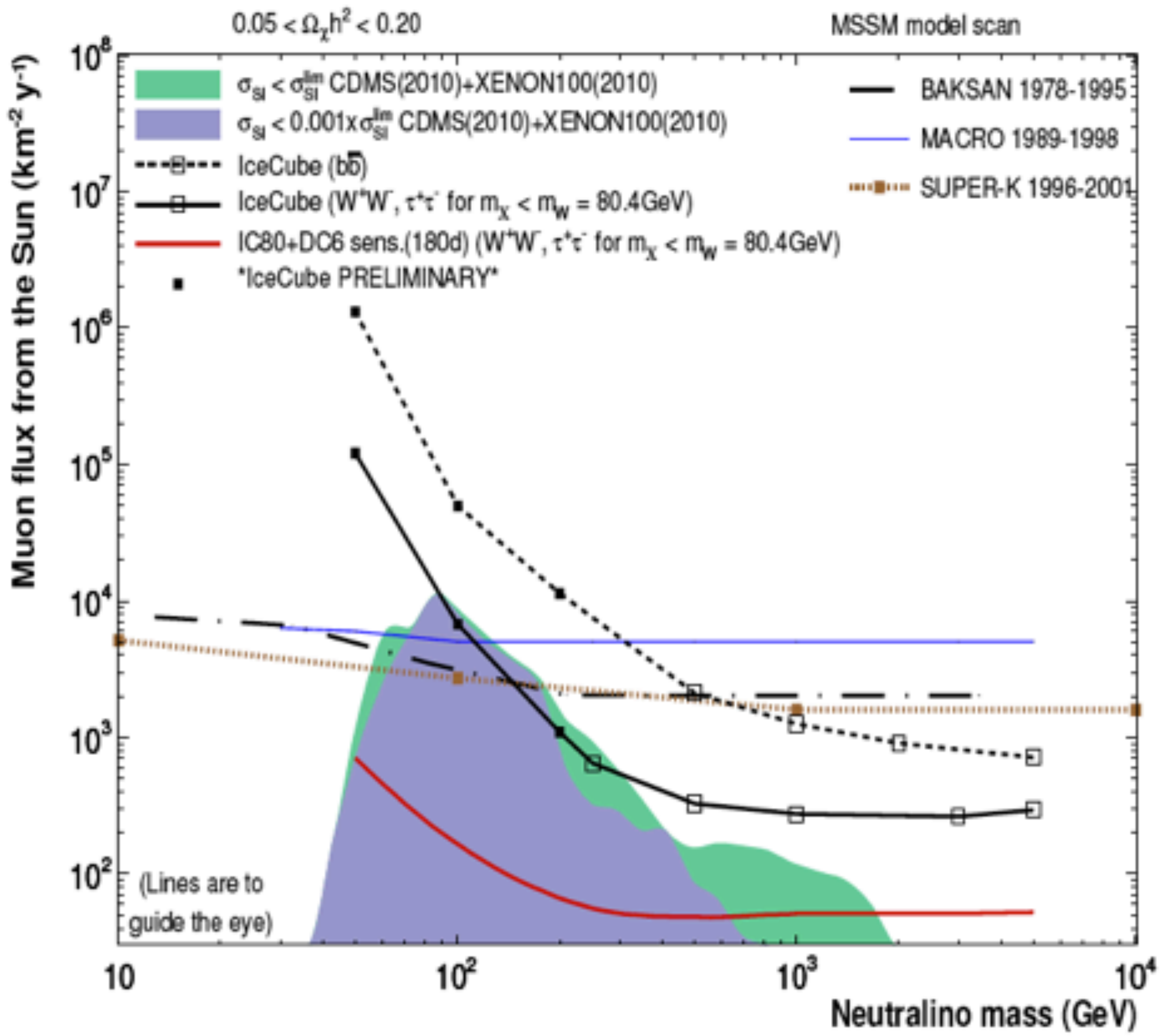
- As sun sweeps through dark matter halo, WIMPs can undergo collisions with nuclei and become gravitationally trapped. Eventually these thermalize, and the rate of capture is balanced by the rate of annihilation (and perhaps evaporation).

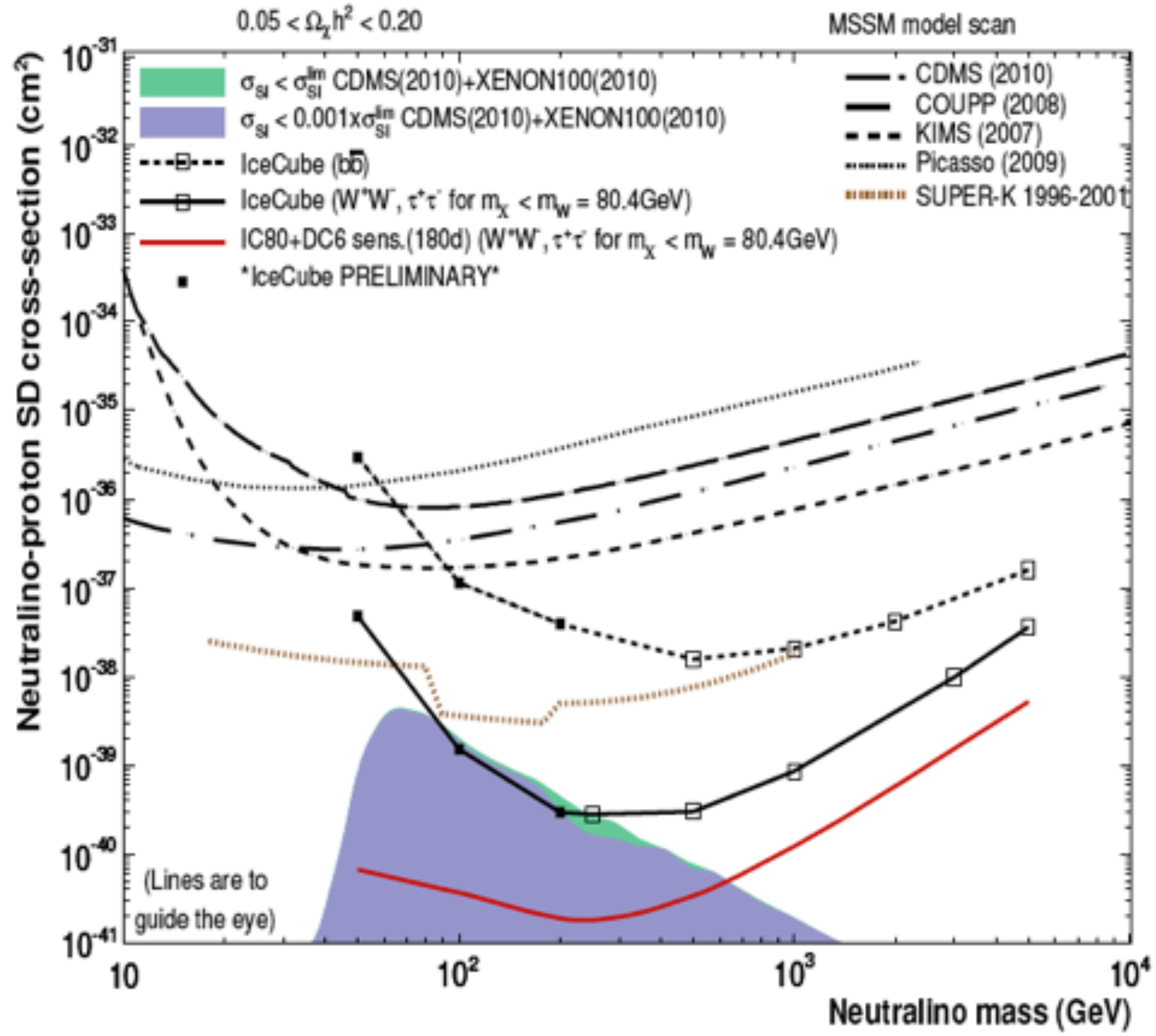
- Existing Amanda, SuperK and other limits

- DeepCore extension of ICECUBE, adding 6 additional strings and pushing the muon detection threshold down to 10 GeV



DM Neutrinos from the Sun





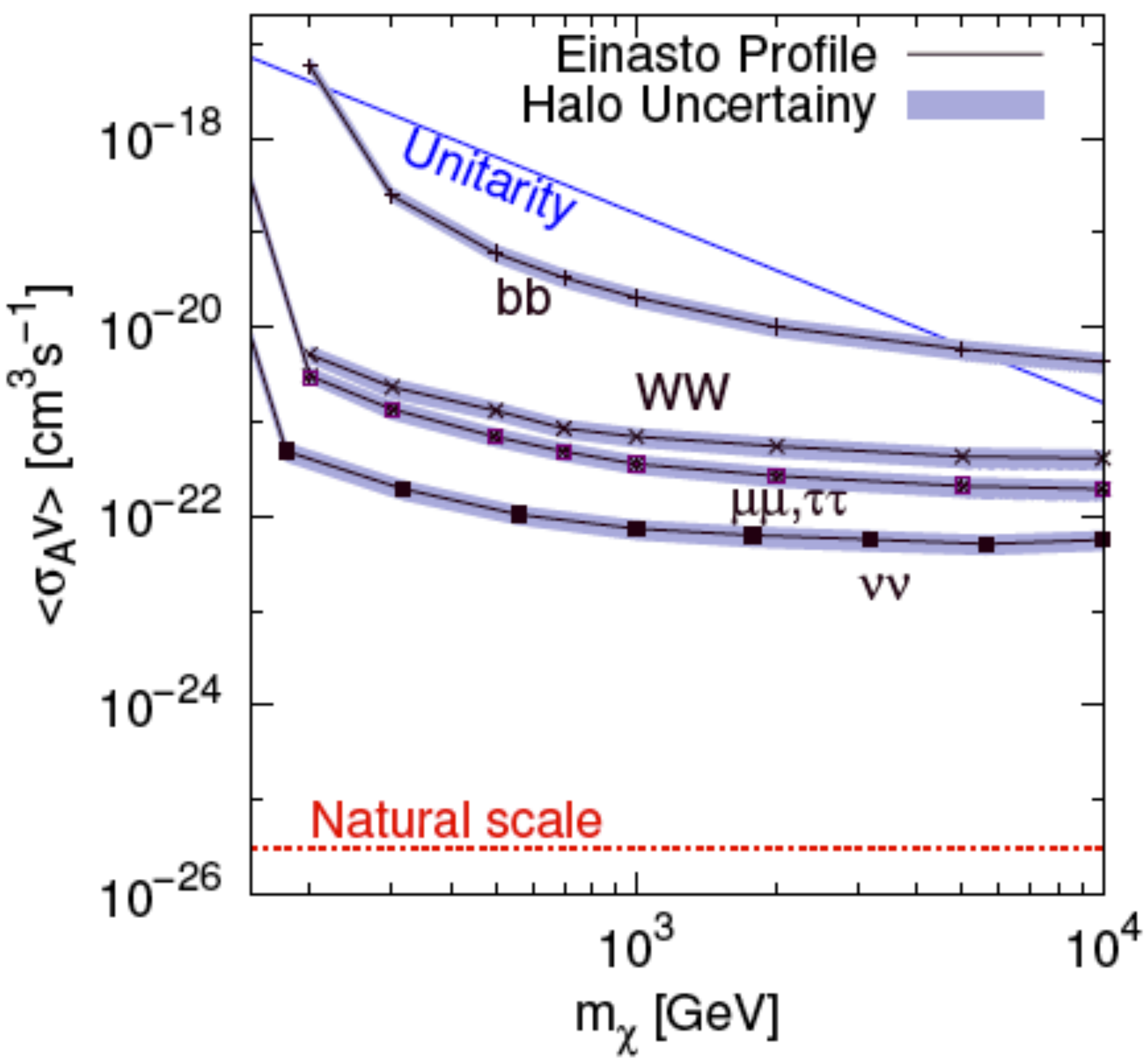
de los Heros for the IceCube Collaboration, Dec 2010, arXiv:1012.0184

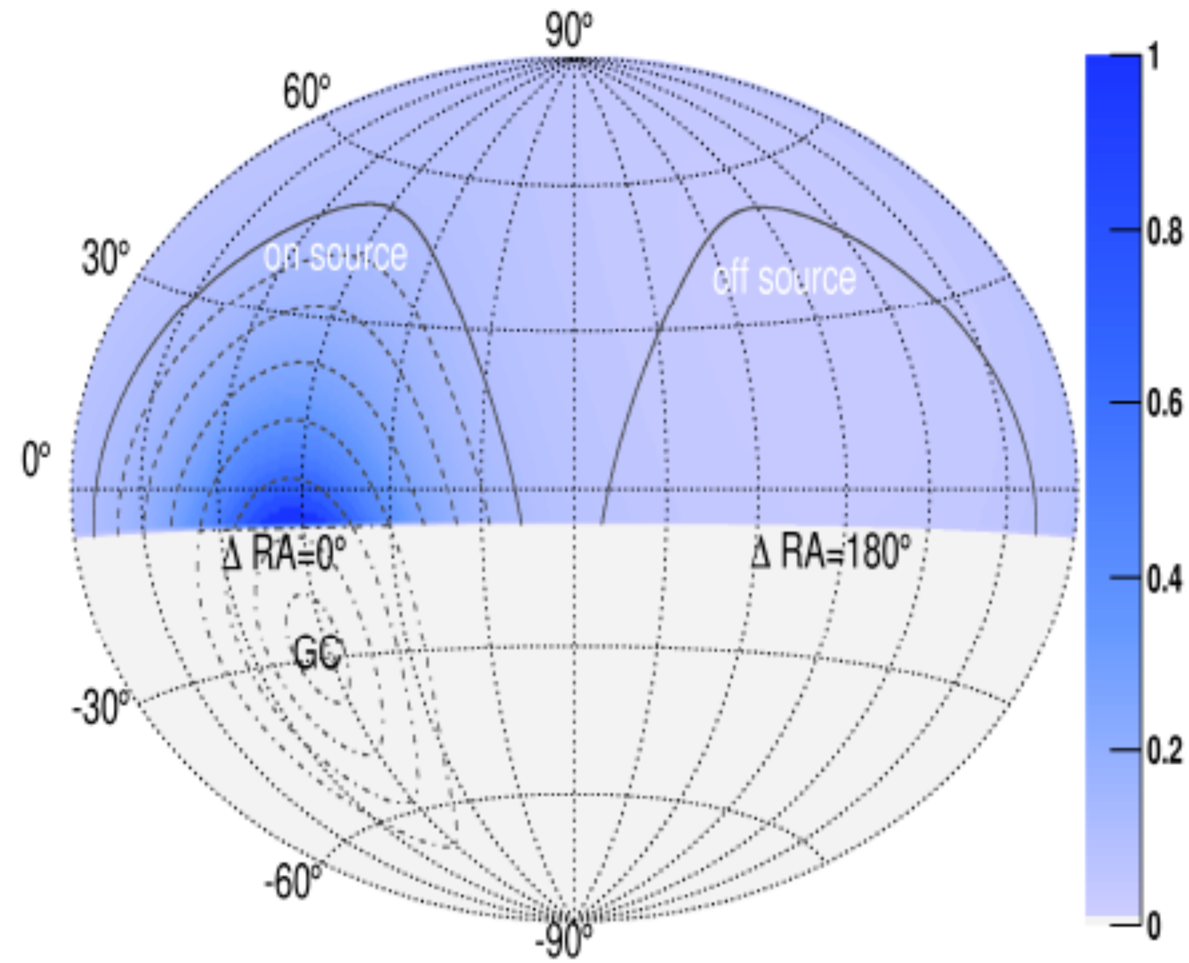
- Limits on the DM annilation flux and Spin-Dependent wimp-nucleon cross-section from IceCube compared with Direct detection limits
- In red, expected improvement in sensitivity with the addition of the six-string Deep Core detector

Neutrinos from GC Region

$$J(\psi) = \int_0^{l_{\max}} \frac{\rho^2(\sqrt{R_{\rm sc}^2 - 2lR_{\rm sc}\cos\psi + l^2})}{R_{\rm sc}\rho_{\rm sc}^2}$$

$$\frac{d\phi_\nu}{dE} = \frac{\langle\sigma_A v\rangle}{2} J(\psi) \frac{R_{\rm sc}\rho_{\rm sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE},$$



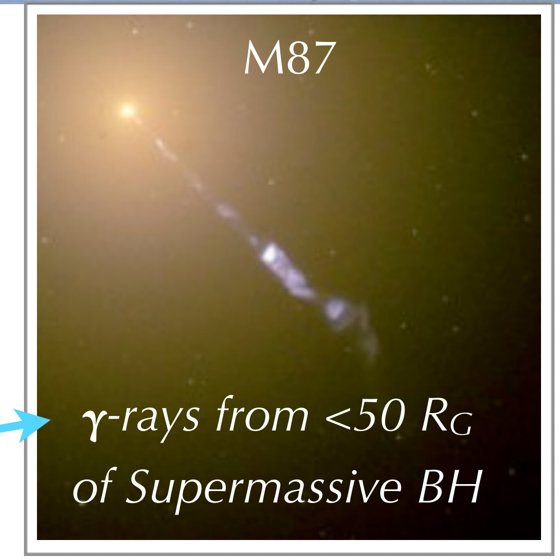


$$\Delta N = \left(N_{\rm on}^{\rm bkg} + N_{\rm on}^{\rm sig}\right) - \left(N_{\rm off}^{\rm bkg} + N_{\rm off}^{\rm sig}\right),$$

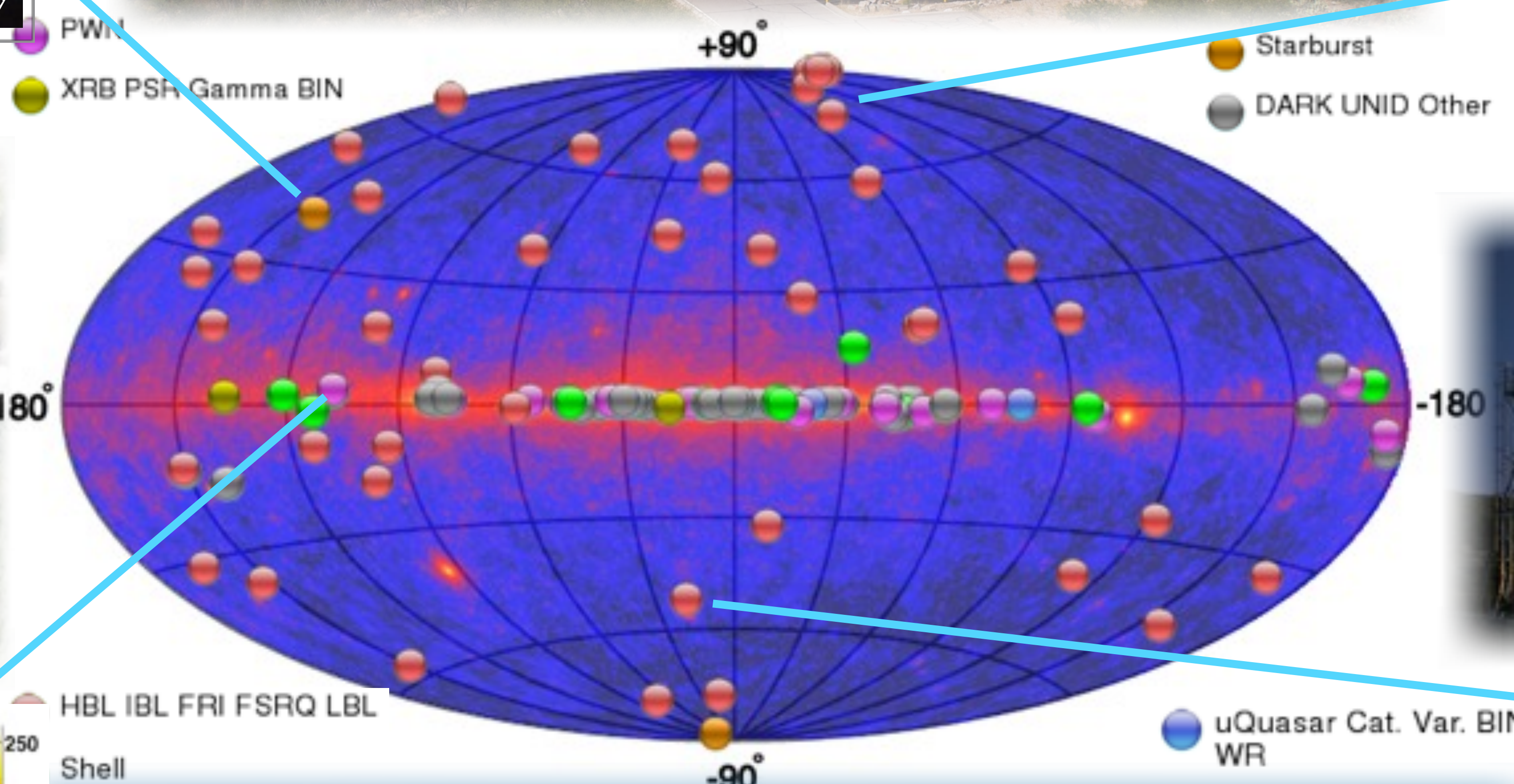
Abbasi et al. (for the ICECUBE collaboration) (Jan 17, 2011 arXiv: 1101.3359)

Gamma-Ray Experiments

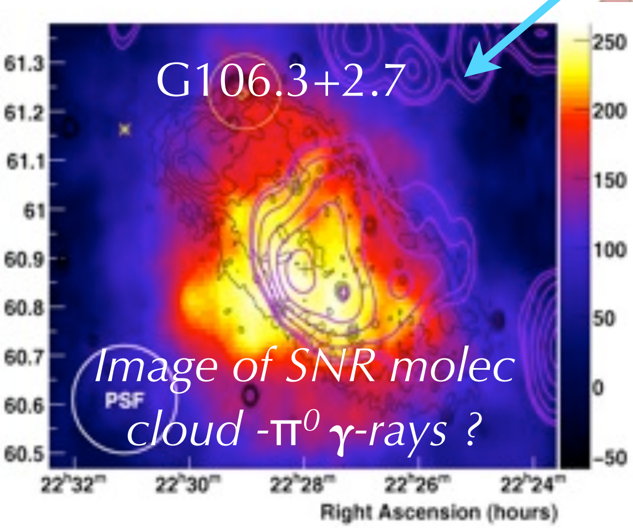
VHE Gamma-Ray Status

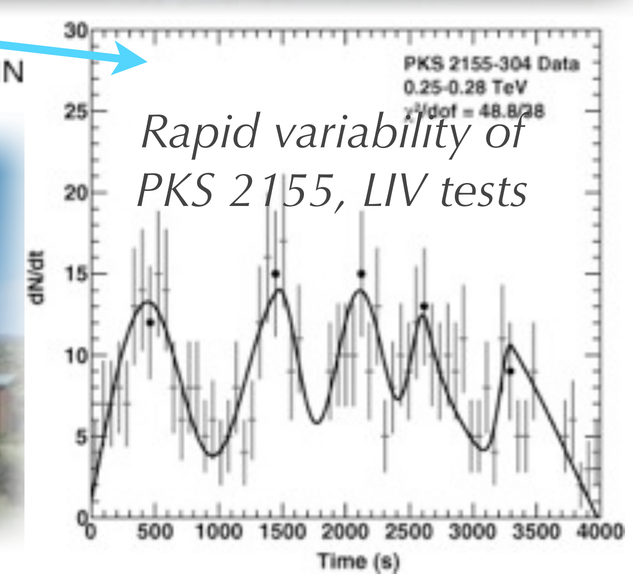


MILAGRO

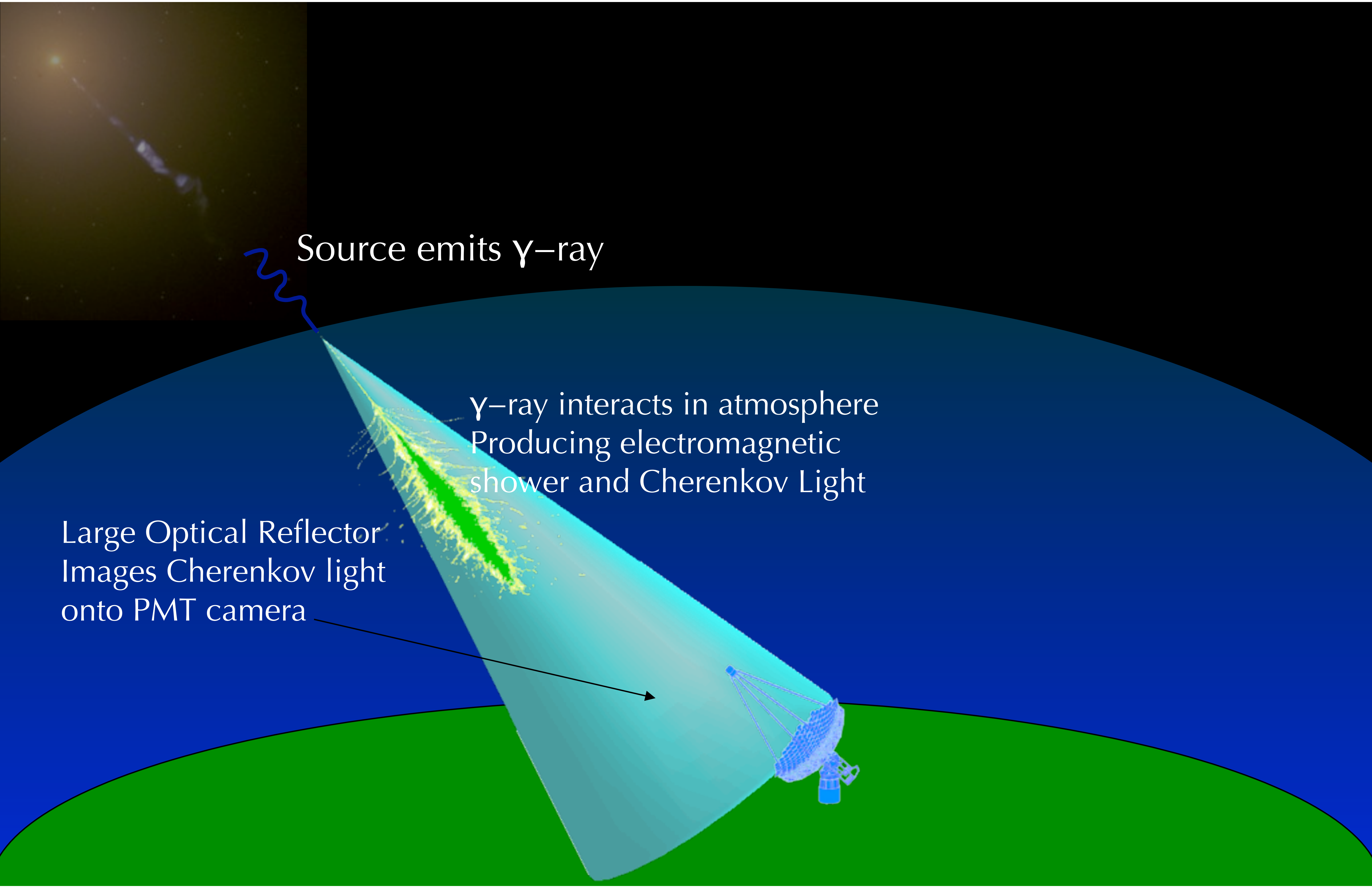


MAGIC





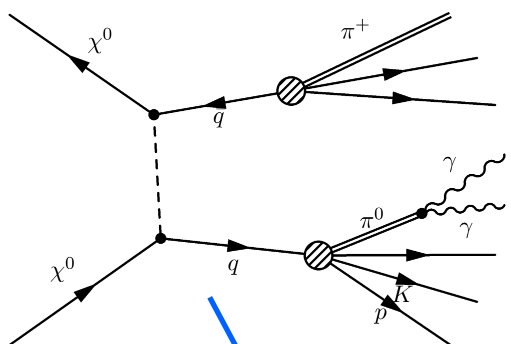
Imaging ACTs

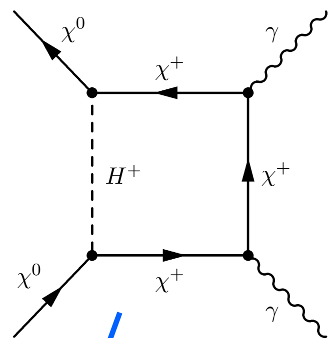


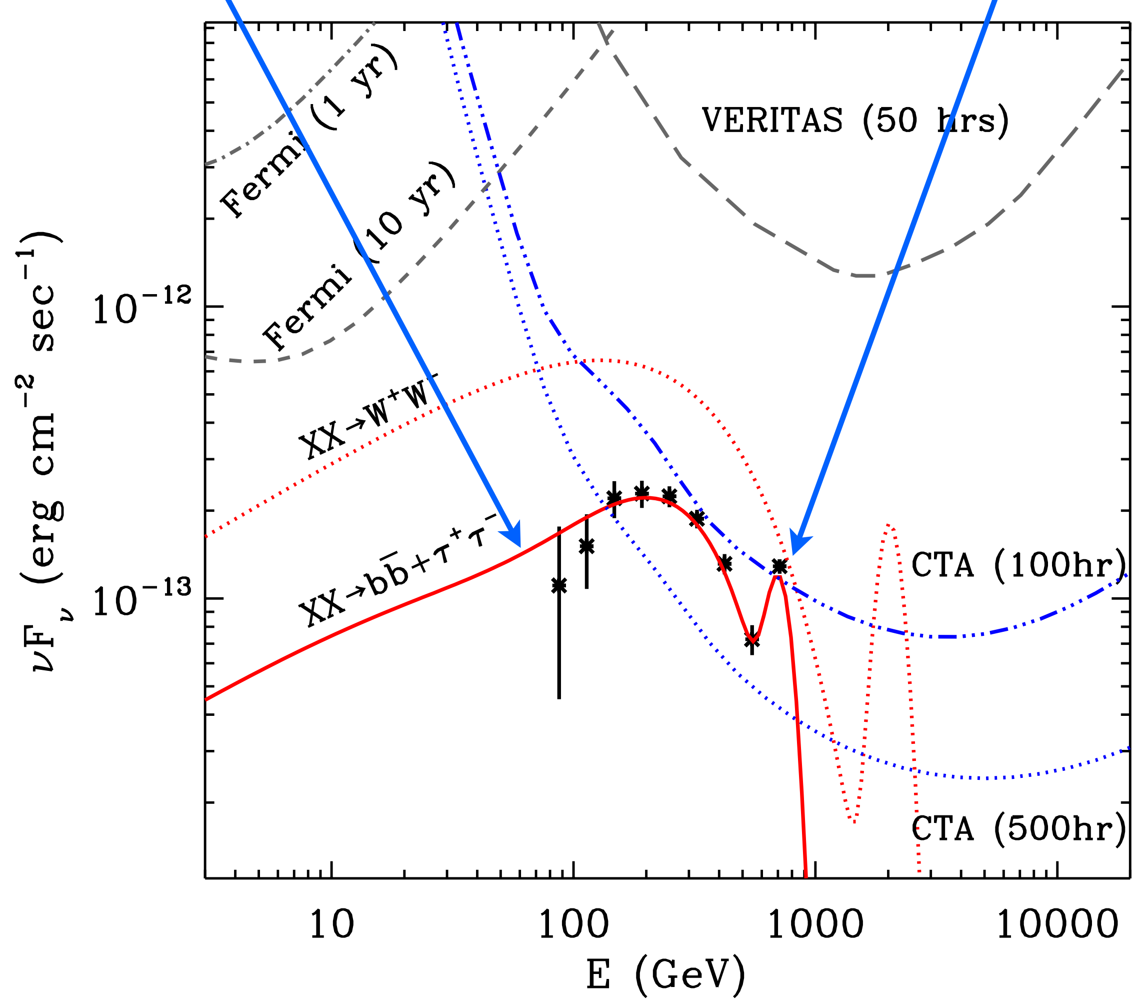
Gamma-rays from DM

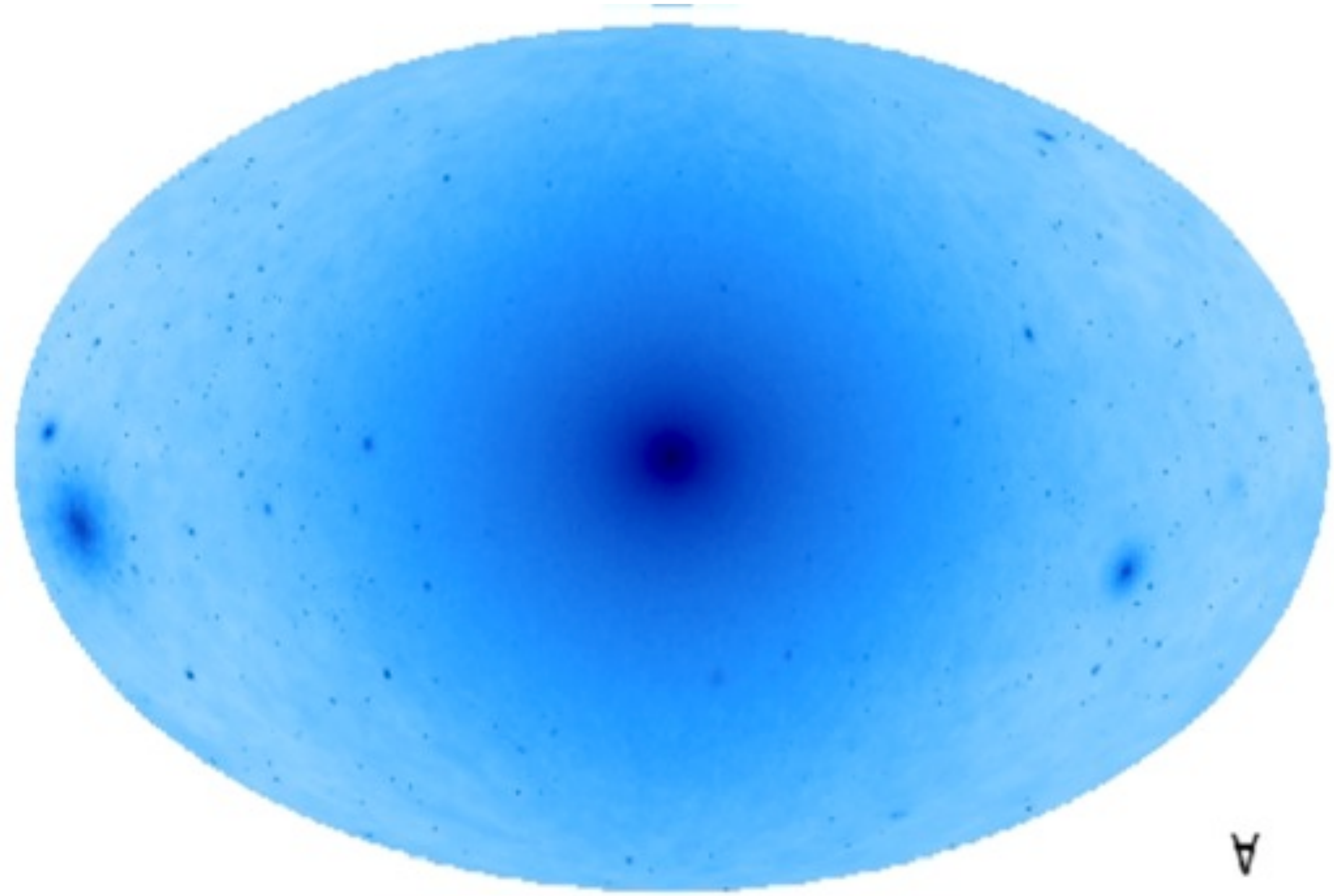
$$E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \underbrace{\left(E_{\gamma,\mathrm{TeV}} \frac{dN}{dE_{\gamma,\mathrm{TeV}}}\right) \left(\frac{\langle \sigma v \rangle}{10^{-26}\mathrm{cm}^{-3}\mathrm{s}^{-1}}\right) \left(\frac{100\,\mathrm{GeV}}{M_\chi}\right)^2}_{\text{Particle Physics Input}} \underbrace{J(\theta)} \; \mathrm{erg\,cm^{-2}s^{-1}sr^{-1}}$$

$$J(\theta) = \underbrace{\frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} \rho^2(l)\,dl(\theta)}_{\text{Astrophysics/Cosmology Input}}$$





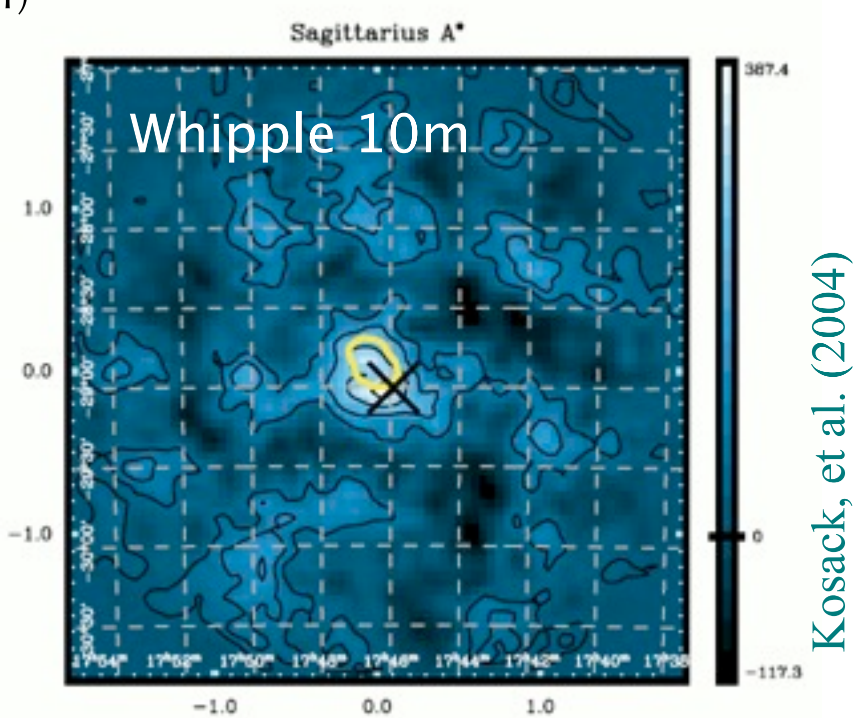




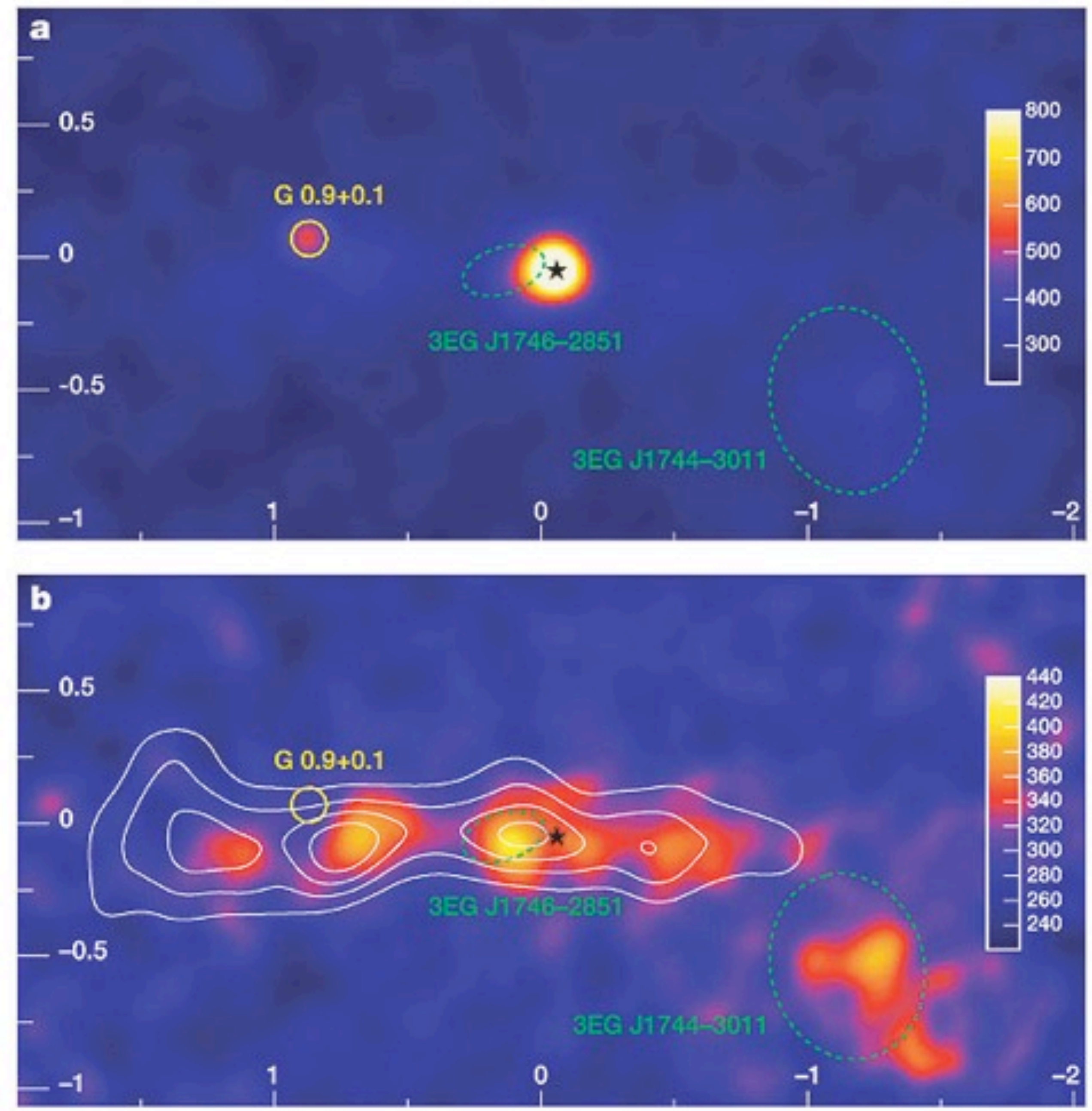
Line-of-sight integral of ρ^2 for a Milky-Way-like halo in the VL Lactea II ΛCDM N-body simulations (Kuhlen et al.)

Galactic Center Region

- **EGRET:** 3EG J1746-2851 (Hartman et al. 1999)
- **Whipple 10m (1995-2003, LZA)** - Evidence for GC at 3.7 std. dev., flat spectrum source (Kosack et al. ApJ, 608, L97 2004)



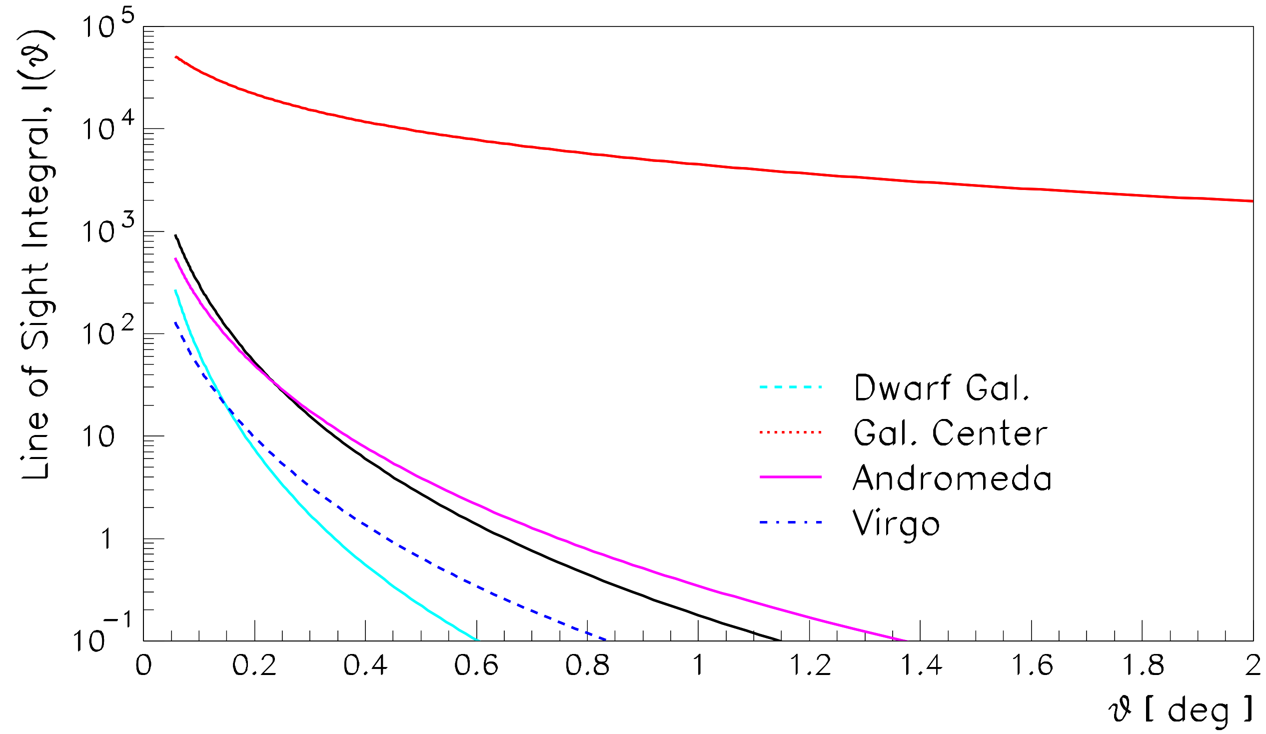
- **H.E.S.S. (2004-2006)** - Now >60 std. dev, $dN/dE \sim E^{-2.1}$ cutoff ~15 TeV, no variability, within 15 arcsec Sgr A*?, PWN? diffuse emission from molec. clouds $dN/dE \sim E^{-2.3}$ (Aharonian et al., 2004, A&A, 425, L13; 2006, Nature, 439, 695)

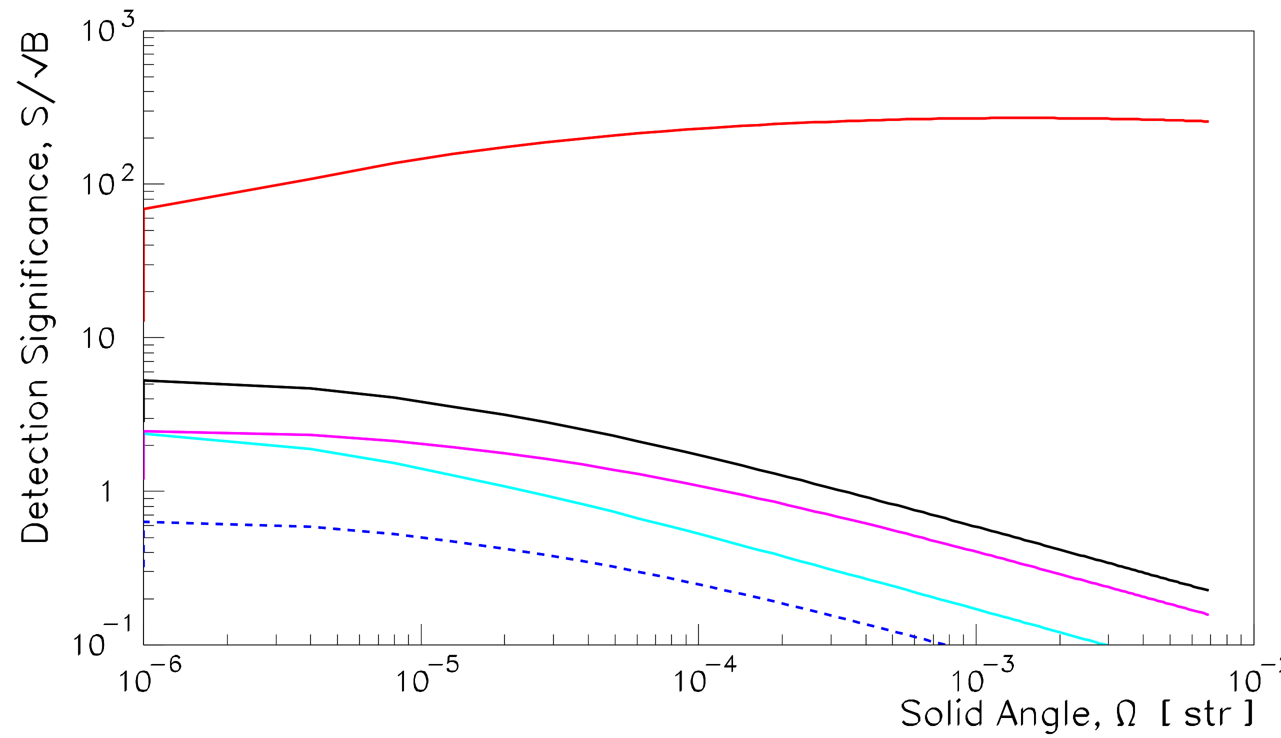


HESS GC region (Aharonian et al., 2006, Nature 439, 695)

Large Astrophysical Backgrounds for DM Search!

Where to Look Next?



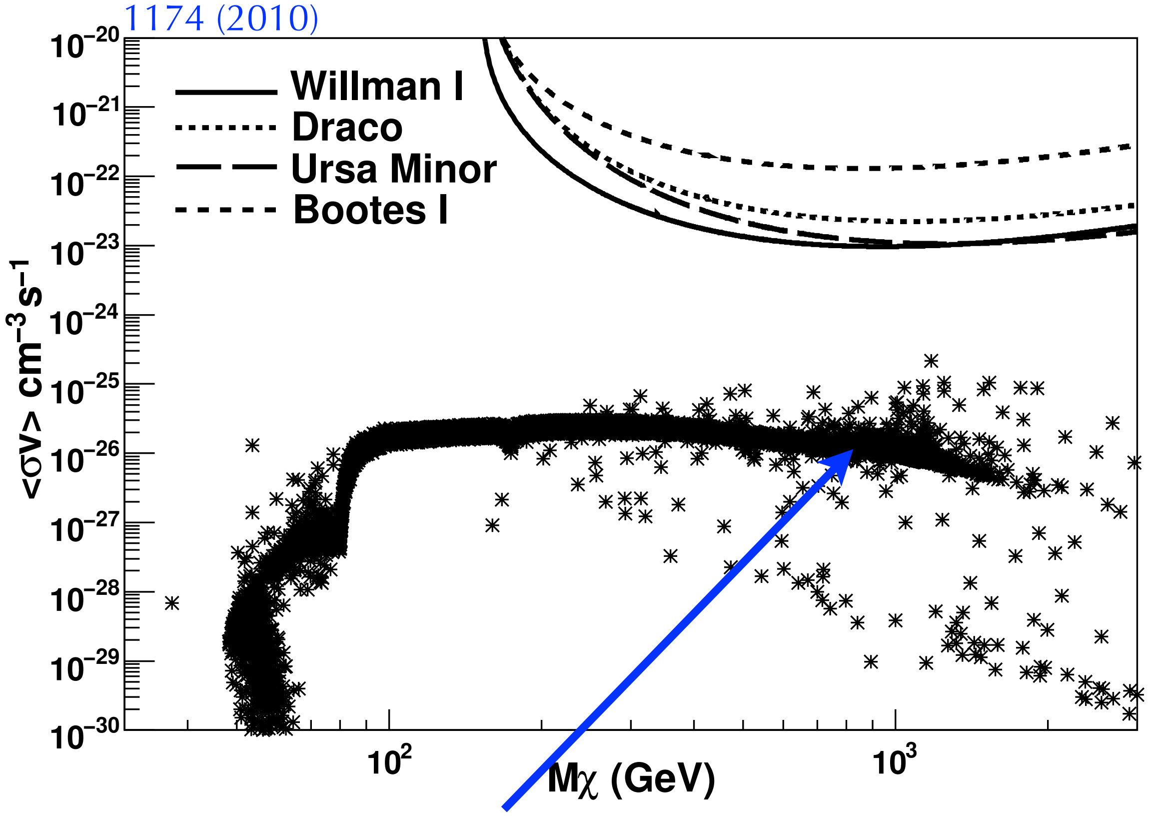


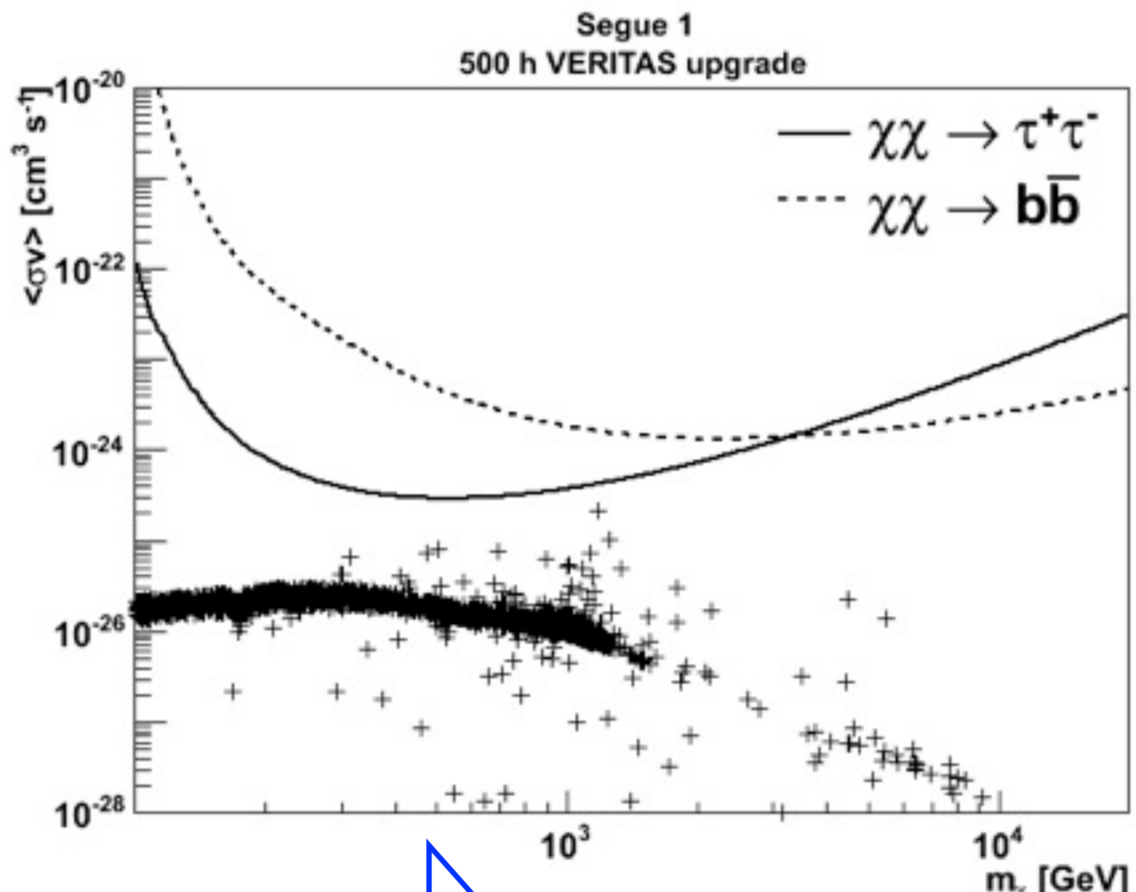
JB 2002

VERITAS Dwarf Limits

Projected Sensitivity

Acciari, V.A. et al. (for the VERITAS collaboration) ApJ, 720, 1174 (2010)





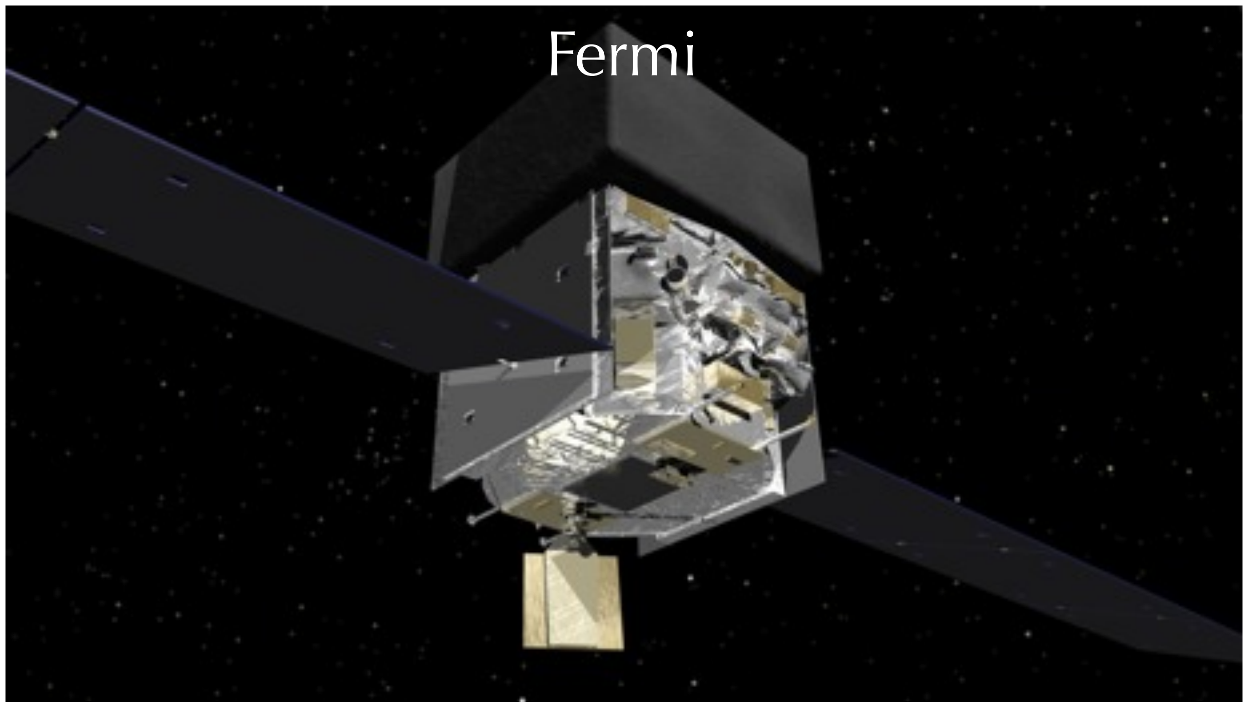
Detection σ ~ decoupling σ⇒ narrow spread

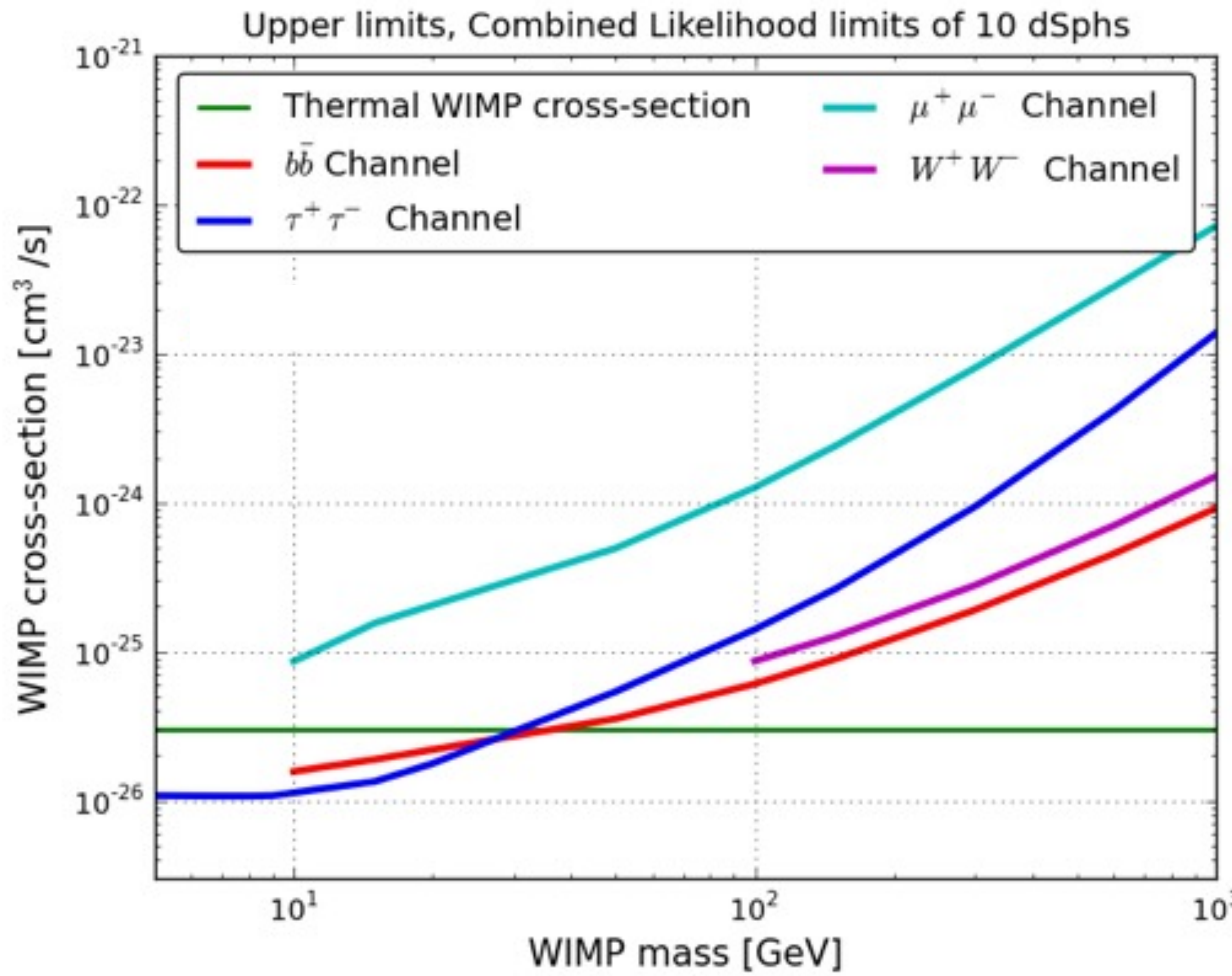
Projected limits for 5 year exposure

- For VERITAS, combining observations of several sources over 5 years will bring upper limits within one order of magnitude of the natural cross section

(SUSY points using DARKSUSY, Gondolo, Edsjo, Bergstrom, Ullio, Schelke, Baltz, Bringmann and Duda)

Dwarf Galaxy Limits



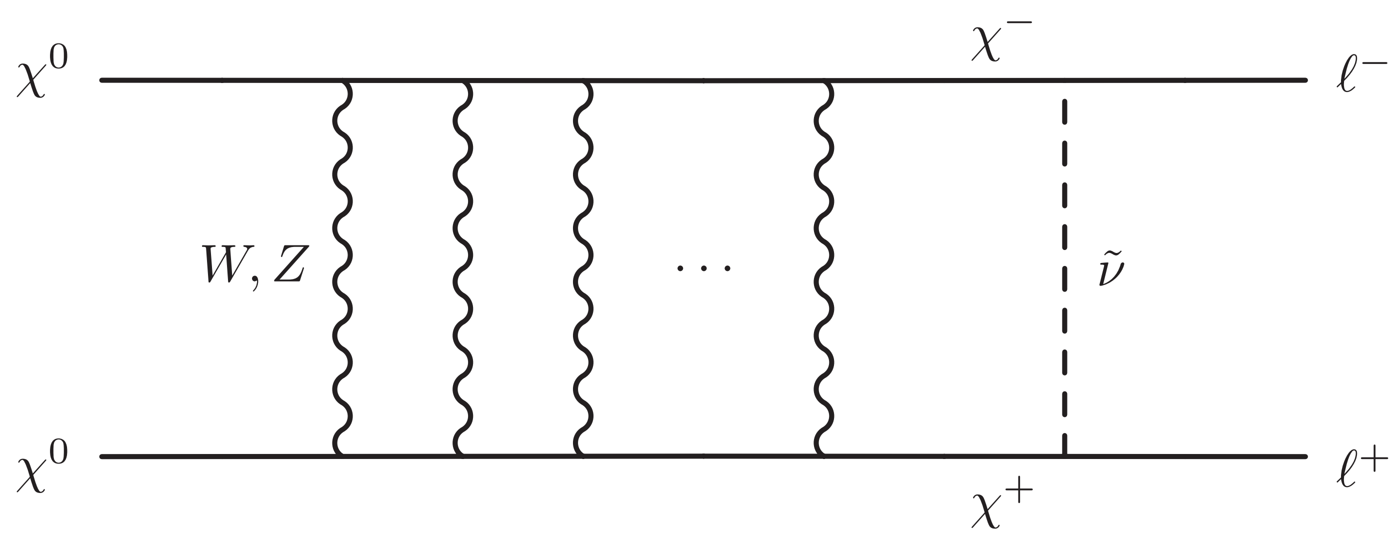


Liena Garde, M., Conrad, J., Cohen-Tanugi, J. for Fermi-LAT Collaboration, Fermi Symposium, May 2011

Stacking Fermi observations of Dwarfs provides constraints of the natural cross section below ~30 GeV.

W/Z Sommerfeld Enhancement

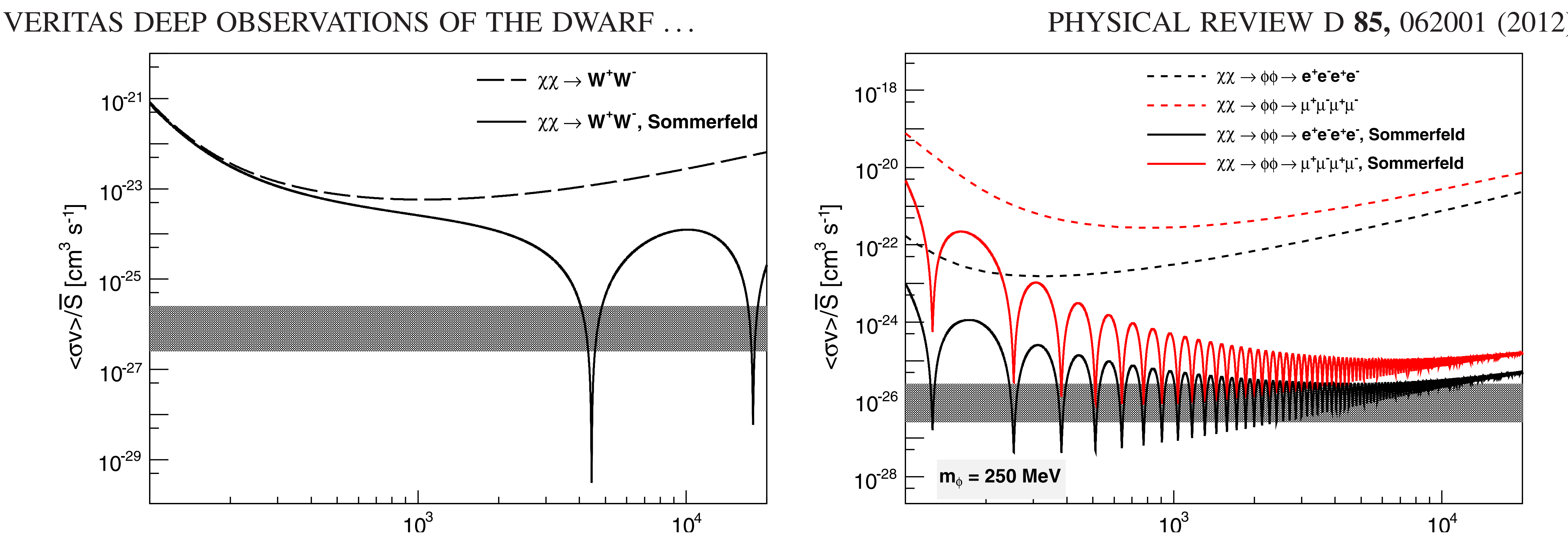
At sufficiently high neutralino masses, the W and Z can act as carriers of a long-range (Yukawa-like) force, resulting in a velocity dependent enhancement in cross section ($1/v$ or even $1/v^2$ enhancement near resonance)



Lattanzi and Silk, PRD 79, 083523 (2009), Profumo (2005)

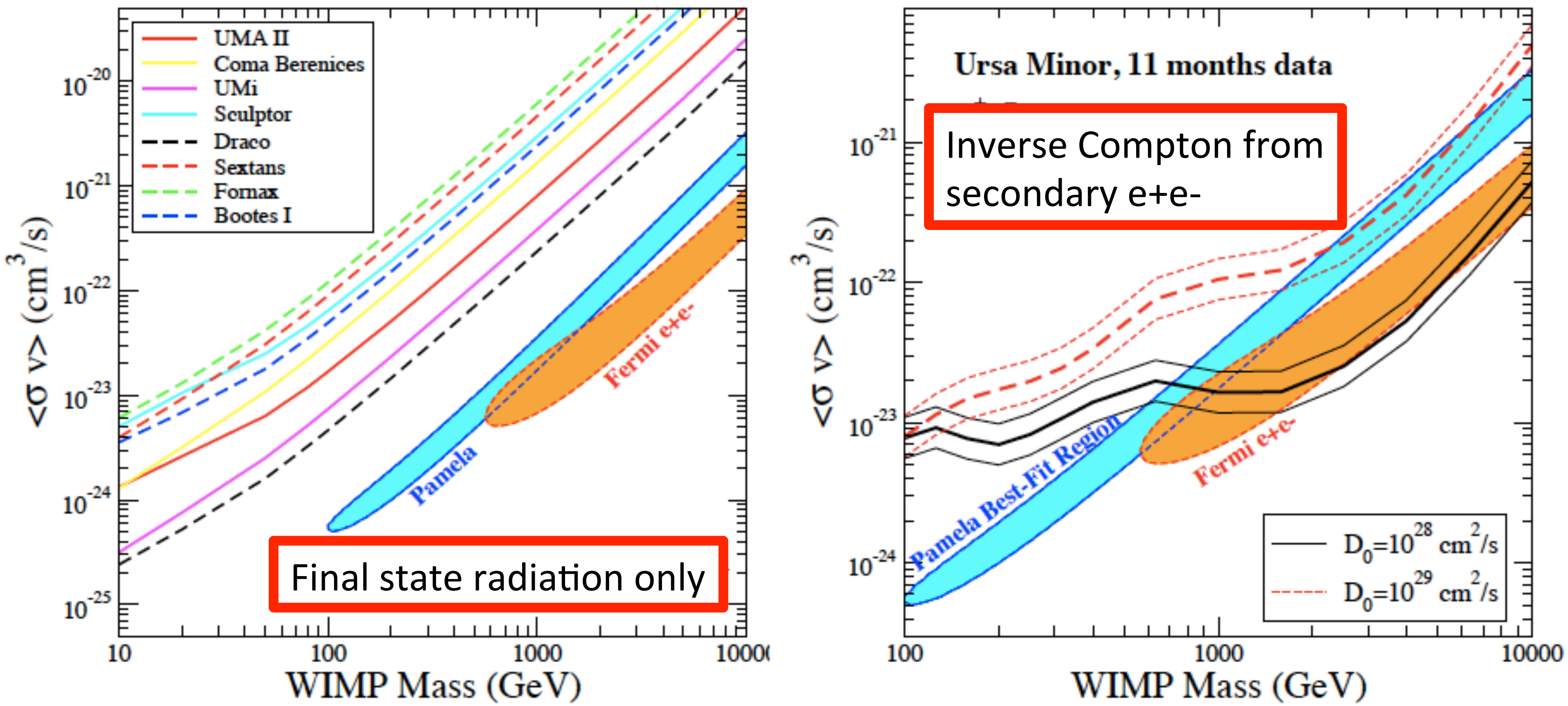
- At high mass, expect Sommerfeld enhancement from W, Z exchange for standard neutralinos can give large enhancement in cross section, larger at small velocities in smaller halo substructure (e.g., Dwarfs)

VERITAS Segue I Results



VERITAS limits on Segue I are beginning to put very serious constraints on leptophillic scenarios, and are beginning to constrain multi TeV mass neutralinos

IC Limits

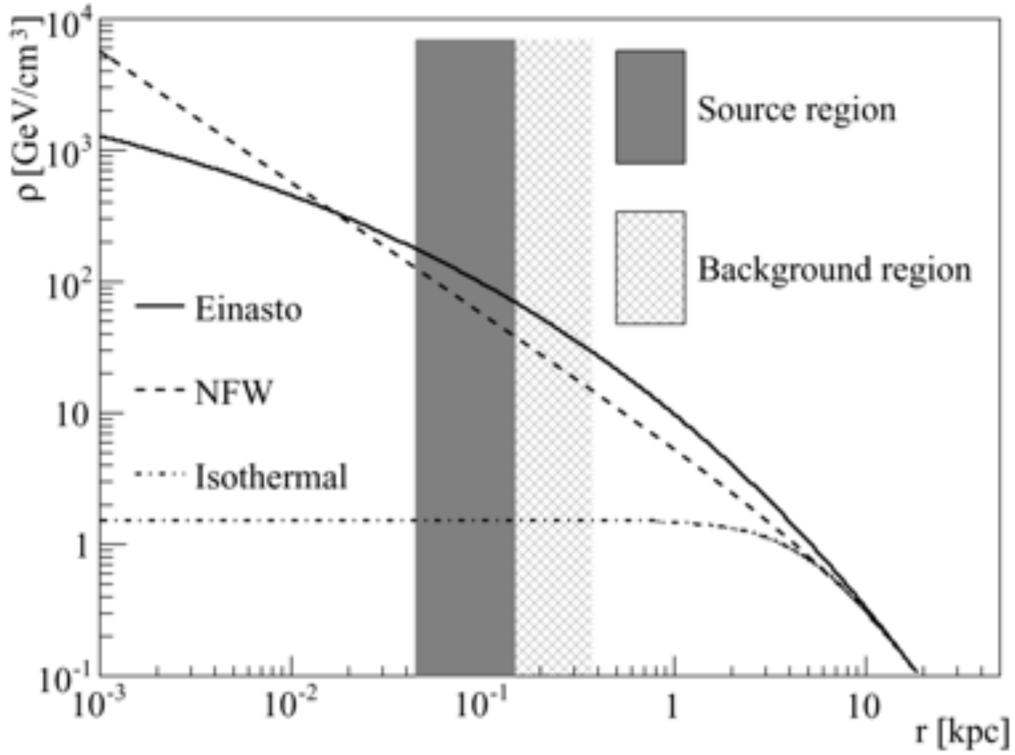


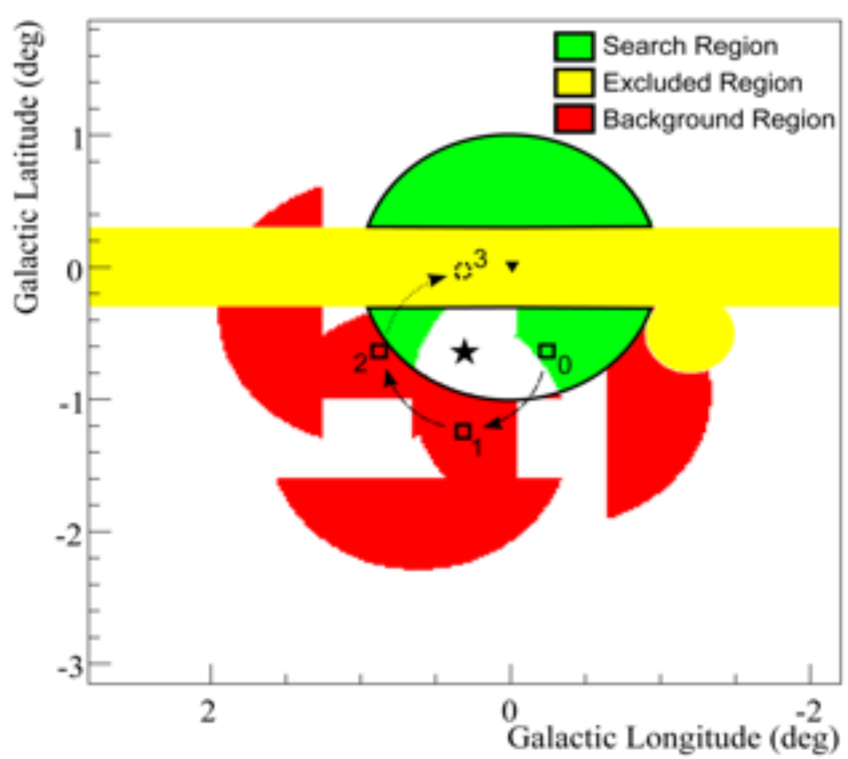
Depending on **diffusion setup**, Inverse Compton emission can kill large mass models

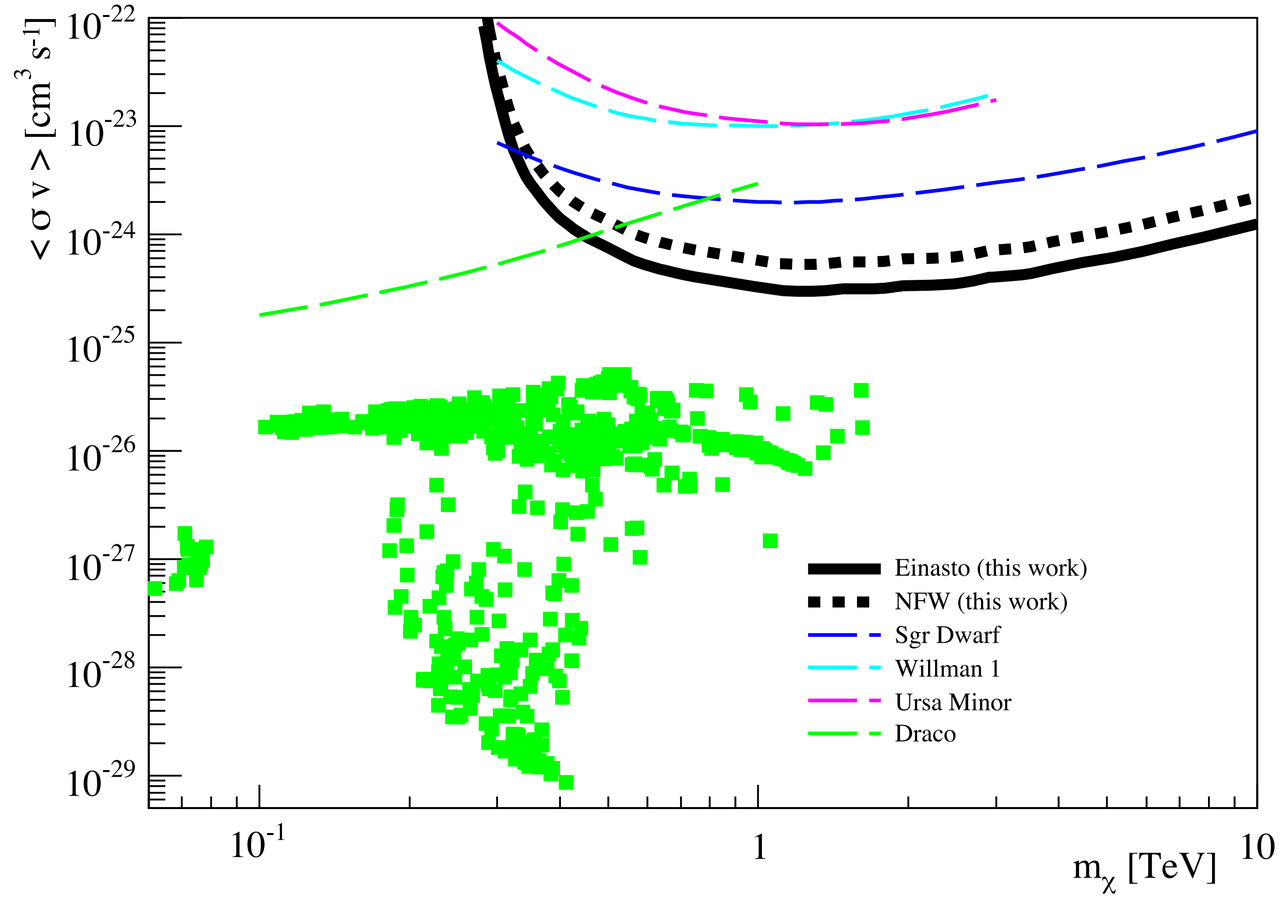
Fermi-LAT Collaboration, APJ 2010, arXiv 1001.4531

(From S. Profumo, APS, 2012)

Galactic Center Revisited

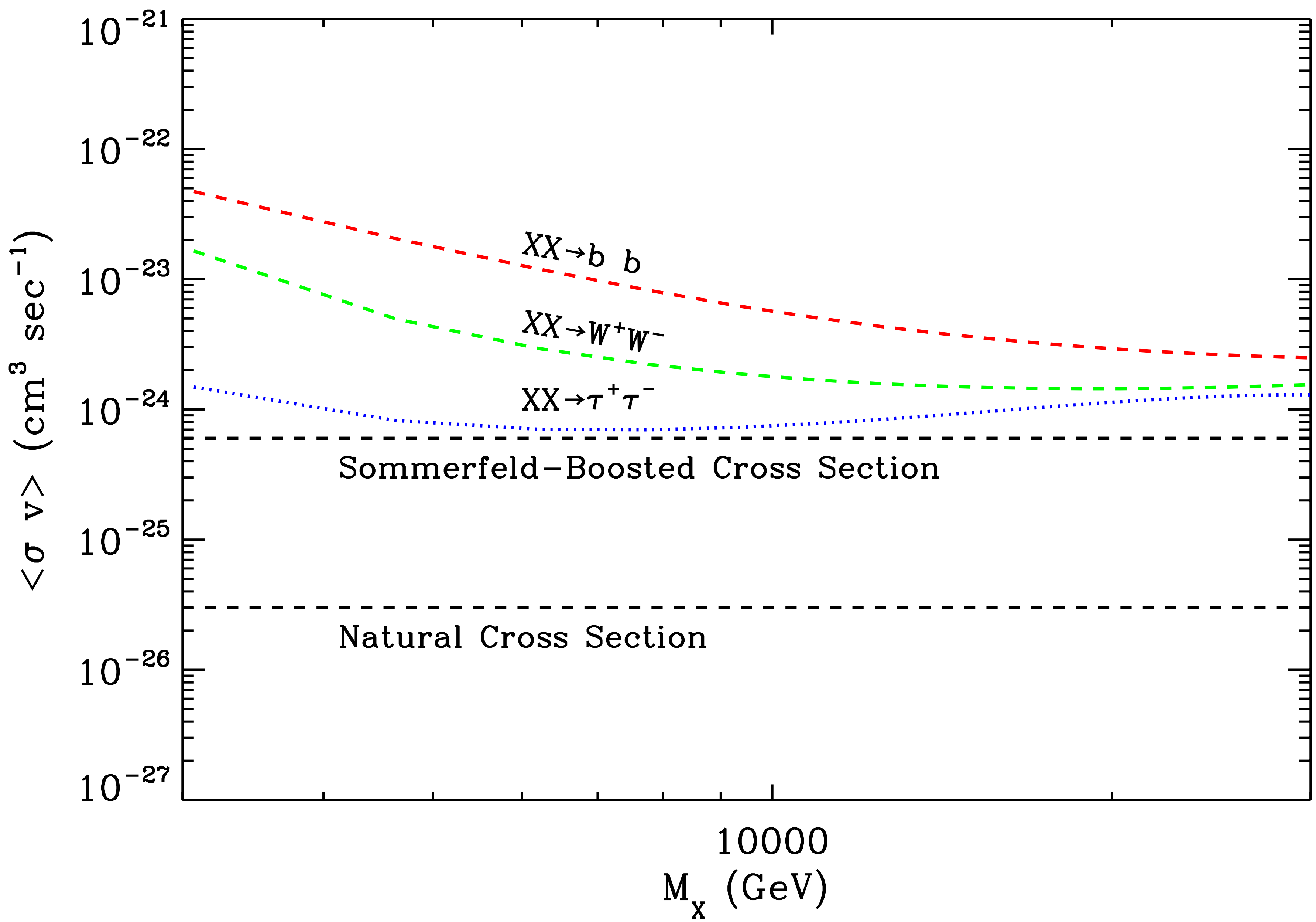






- Even though bright source at GC, can still get better limits from region around GC (Aharonian et al. for the HESS collaboration, PRL 106, 1301)

Projected VERITAS GC Sensitivity

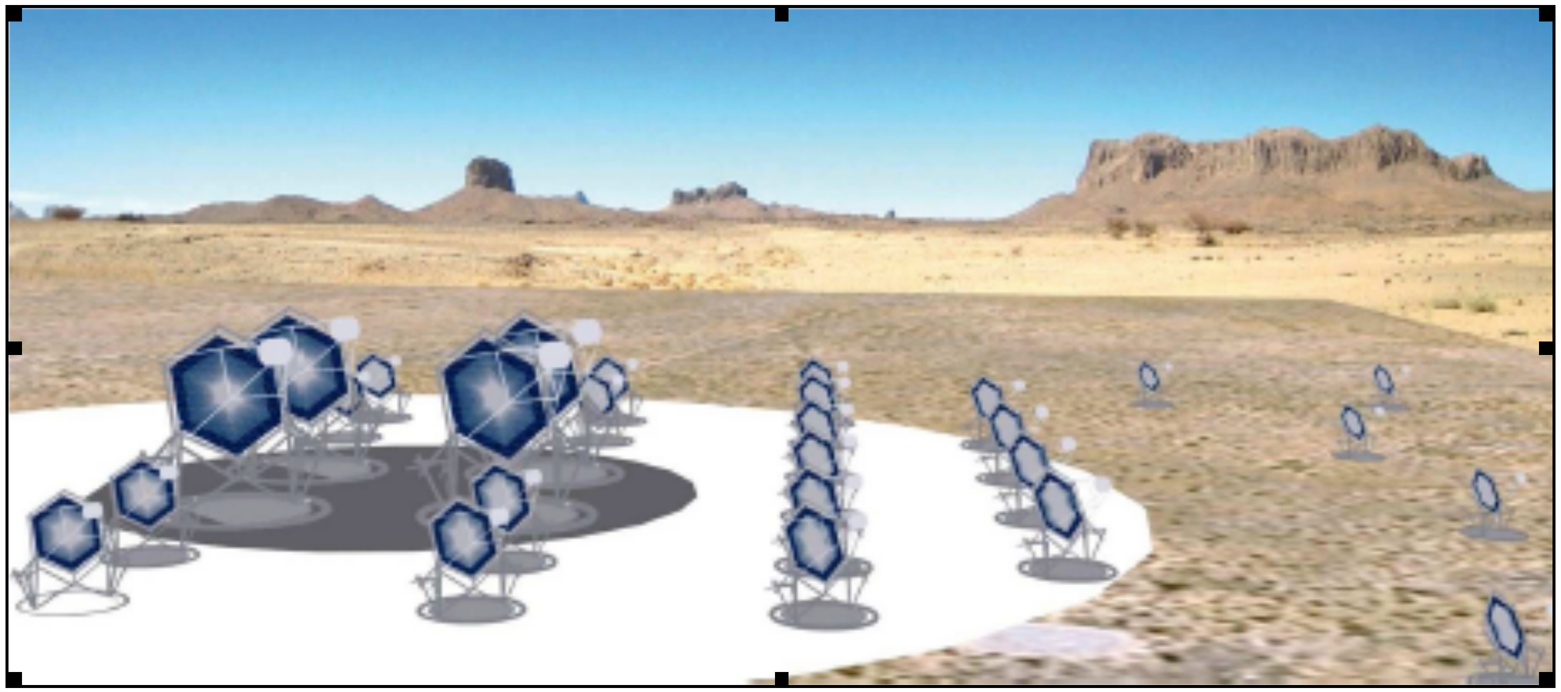


- Estimated upper limits for 5 years of VERITAS LZA data based on probability observed number of counts given NFW halo convolved with angular resolution, mass-dependent fits to Pythia spectra convolved with energy resolution.

Future Experiments

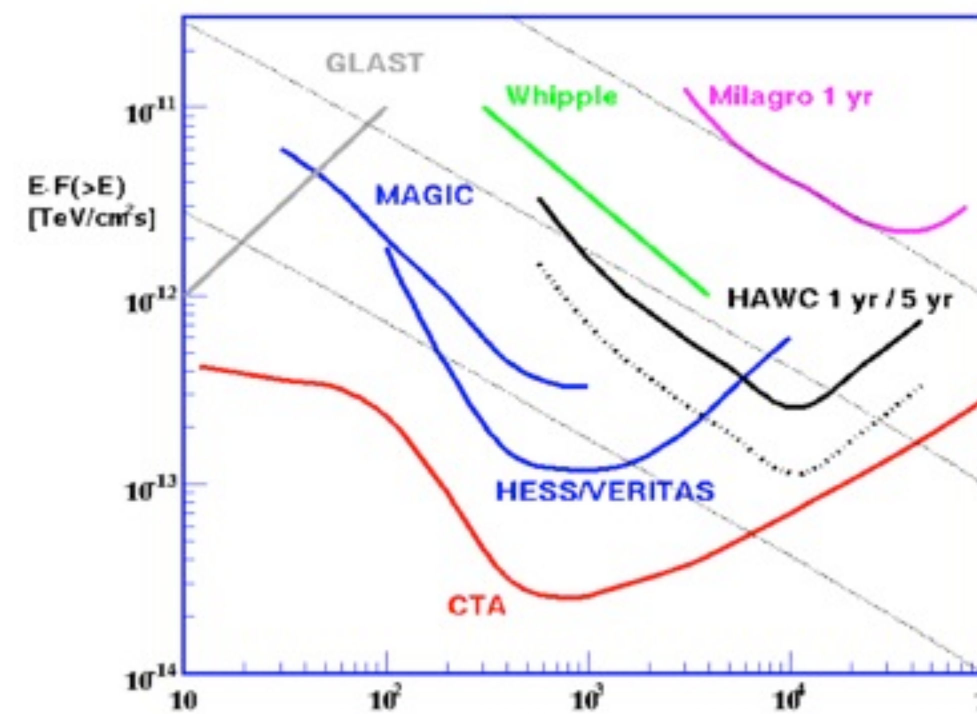
Future Experiments

CTA

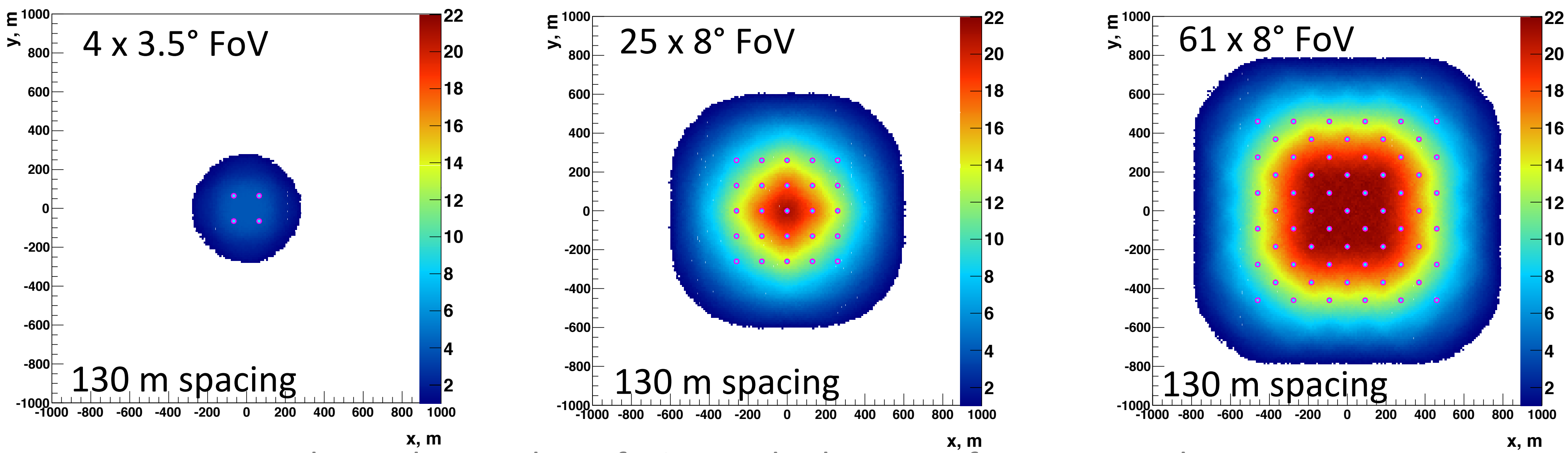


HAWC

- CTA with US contribution will have ~km² area, 8deg FoV, ~arcmin angular resolution, ~10% energy resolution
- CTA graded array design
    - 4 x 24m Large Size Telescopes (LSTs) for the lowest energies
    - 60 x 12m Mid-Size Telescopes (MSTs) for medium energies (100 GeV - 10 TeV)
    - 50 x 6m Small-Size Telescopes (SSTs) for high energies (>10 TeV)
- HAWC will consist of 300 water tanks at 4100m a.s.l to provide all-sky survey observations above TeV energies



US Contribution to CTA



Color scale: number of triggered telescopes for 500 GeV showers

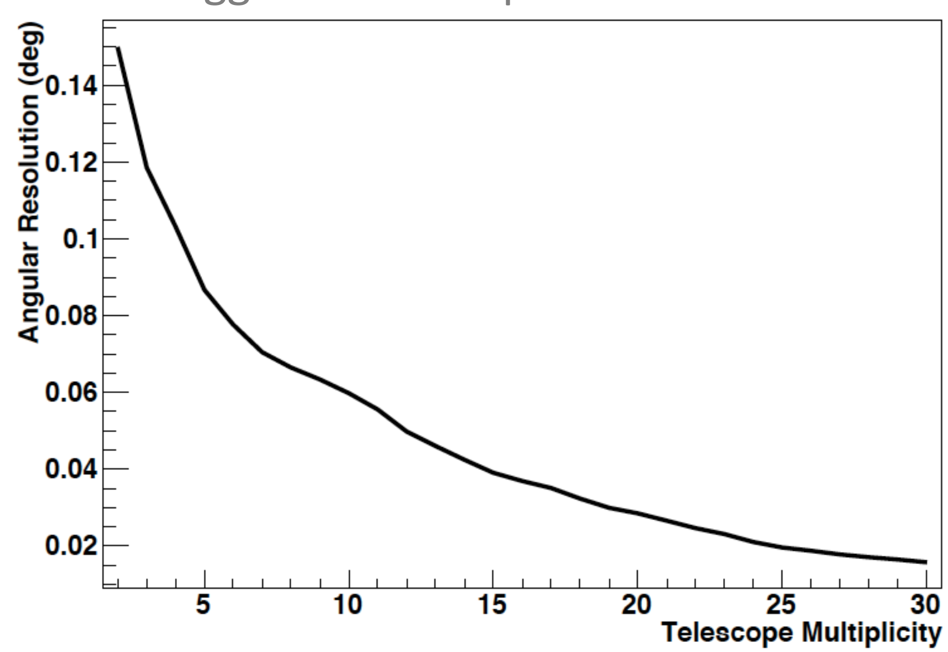
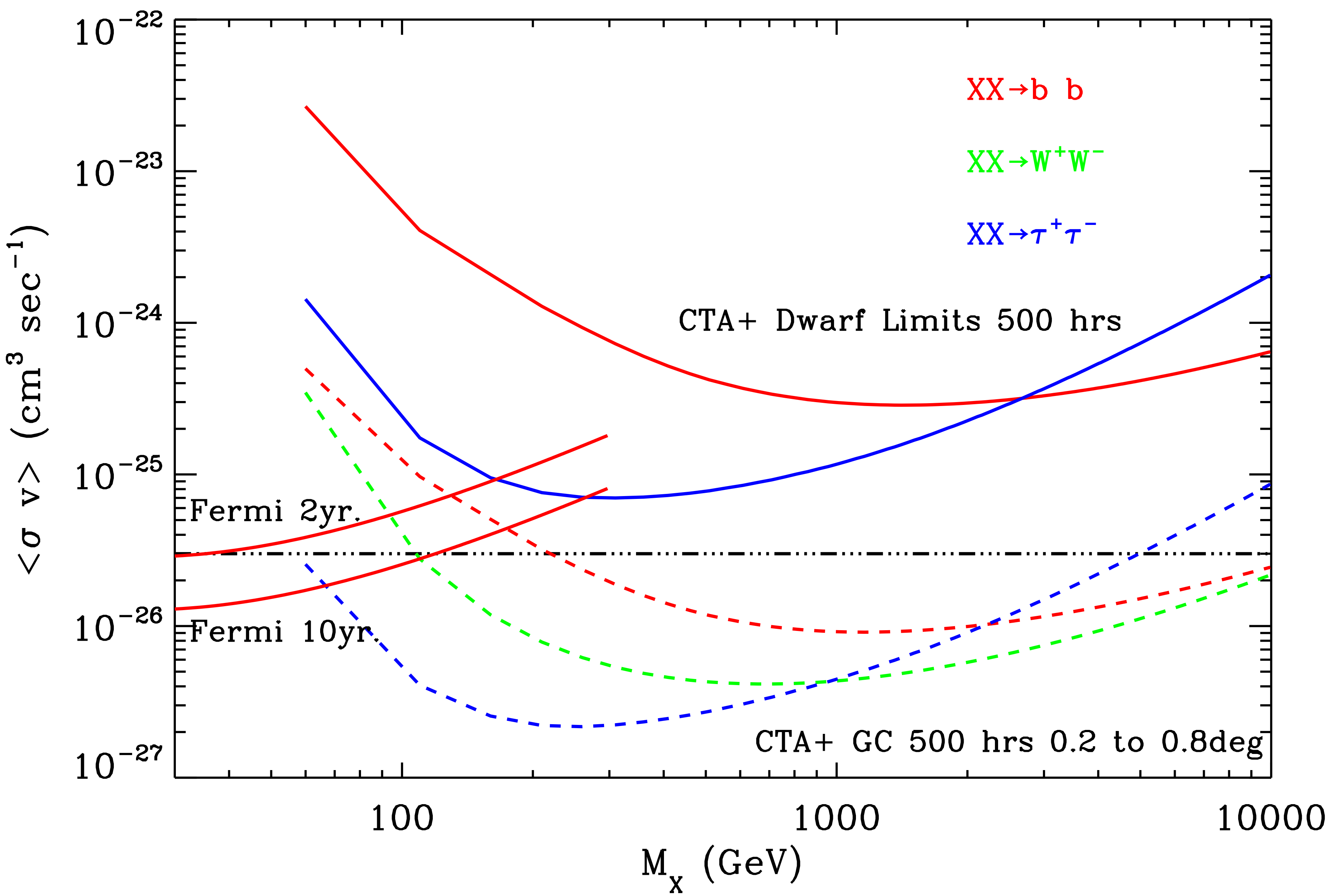


Figure from K. Bernlöhr

The primary goal of the US groups, CTA-US, is to enlarge baseline MST array of CTA by additional 36 telescopes and boost sensitivity and angular resolution of CTA Southern Array.

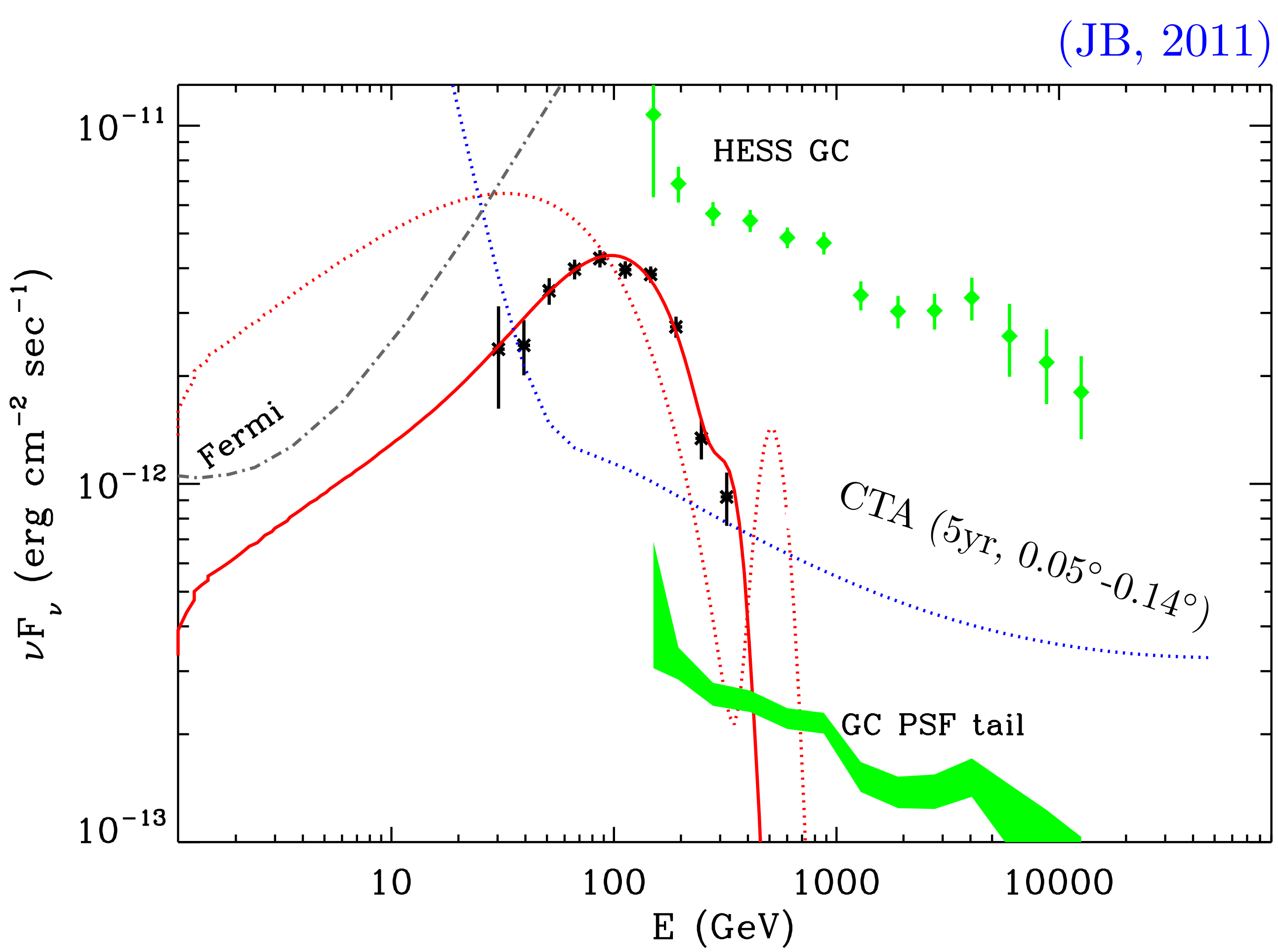
Estimated CTA+ Sensitivity



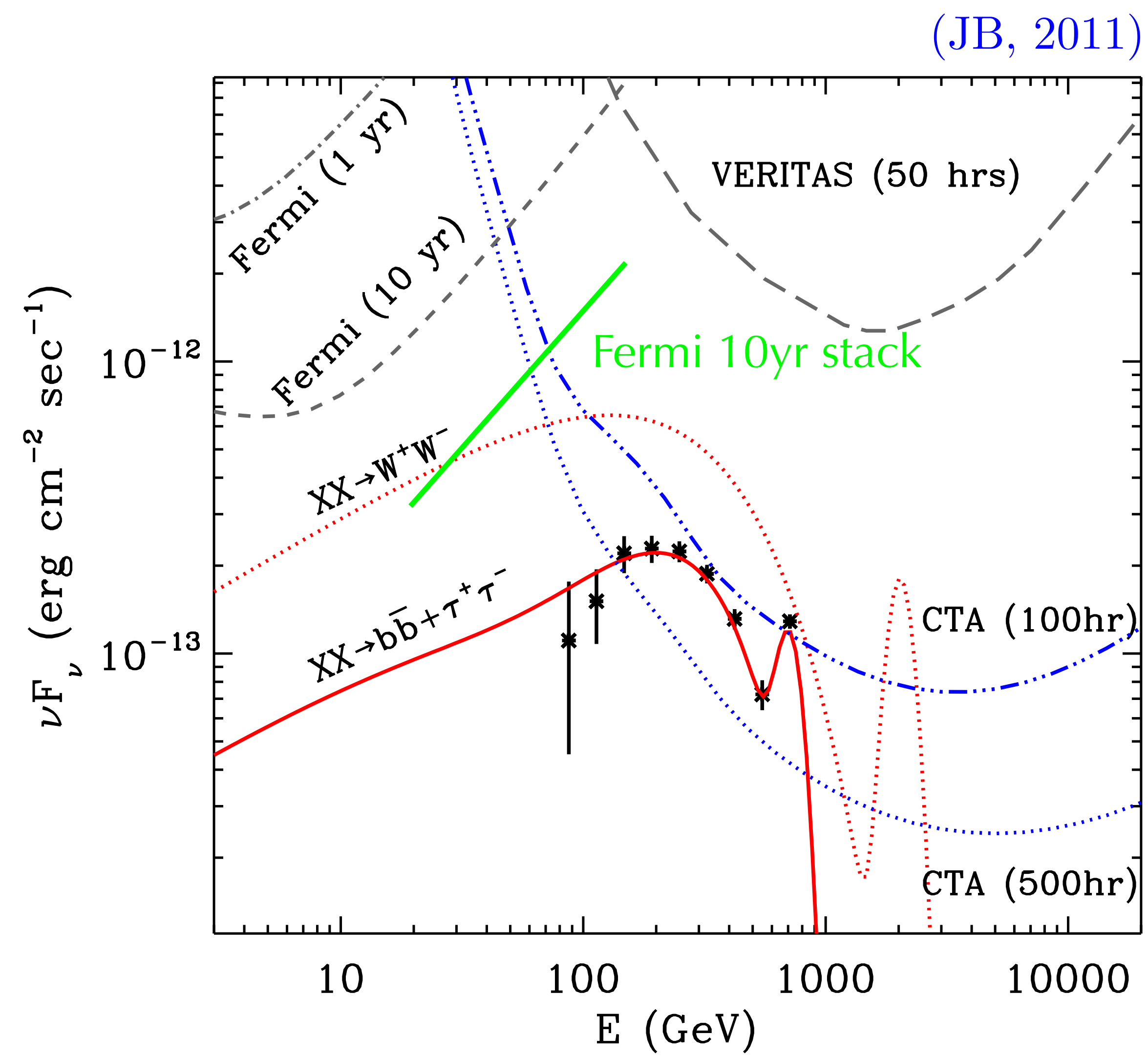
Conservative estimate of Fermi 10yr and CTA sensitivity, assuming no boost, and conservative estimate of CTA+US performance

GC DM Prospects

GC with Future ACT



Dwarf Galaxy with Future ACT



- For CTA (a future large ground-based array) lower threshold, improved angular resolution and larger field of view could result in spectral measurements for generic cross-section with no boost (for the GC), and with a modest boost or source stacking for Dwarf galaxies

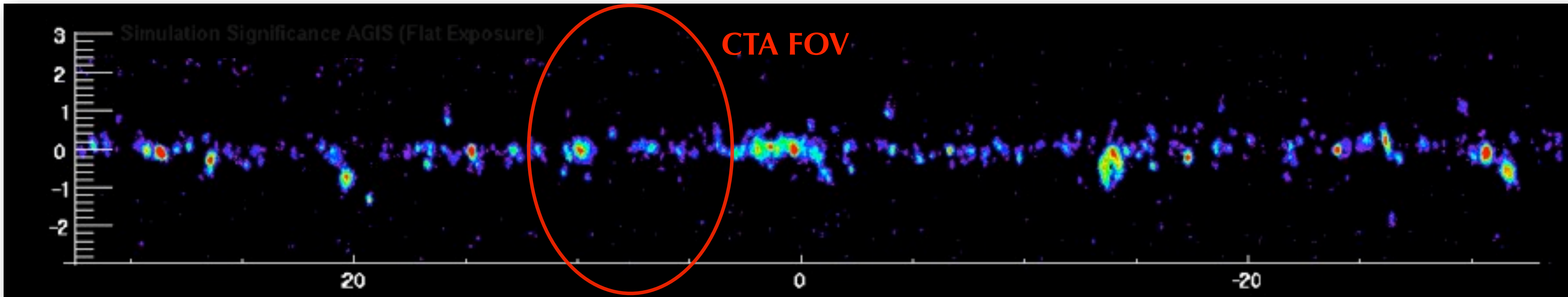
Conclusions

- Electron/Positron measurements show an excess that could be an indication of Dark Matter annihilation, or astrophysical processes. Gamma-ray measurements are close to ruling out the DM scenario.
- Neutrino observations of the sun both with HE arrays (like ICECUBE) and lower-energy water Cherenkov detectors (Super-K) provide interesting constraints on DM annihilation
- Gamma-ray detection cross-section is closely linked to the total annihilation cross-section in the early universe for a thermal relic.
- The *universal* DM annihilation spectrum is imprinted with the particle mass and annihilation channels. Gamma-rays can provide particle ID.
- Gamma-rays could also provide a measurement of the halo distribution linking a new DM particle to structure formation.
- Gamma-ray experiments are still more than an order of magnitude away from natural cross-section, but CTA (with long exposures dedicated to DM studies and U.S. contribution of 36 telescopes) will be sensitive to the natural cross-section for the GC, or to Dwarf Galaxies with a modest boost.

Back-up Slides

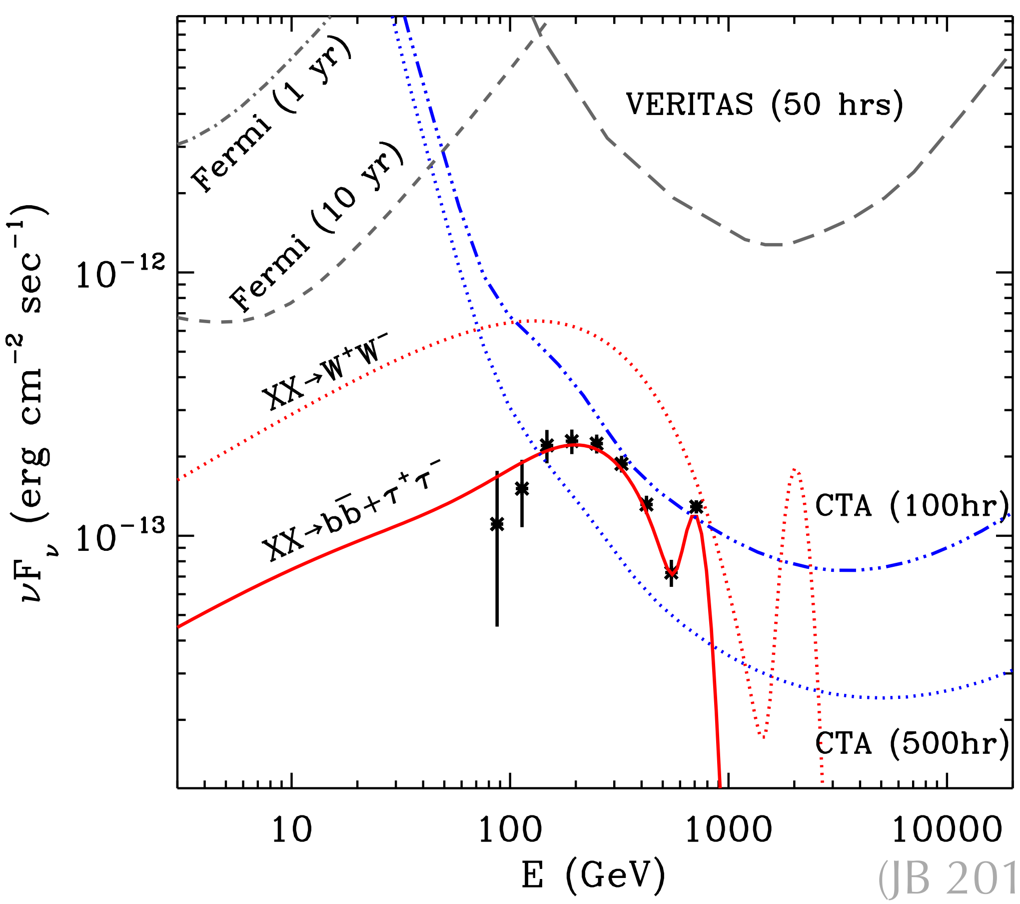
CTA Science Prospects

Wider field of view, better sensitivity, better angular resolution for Astrophysics and DM searches



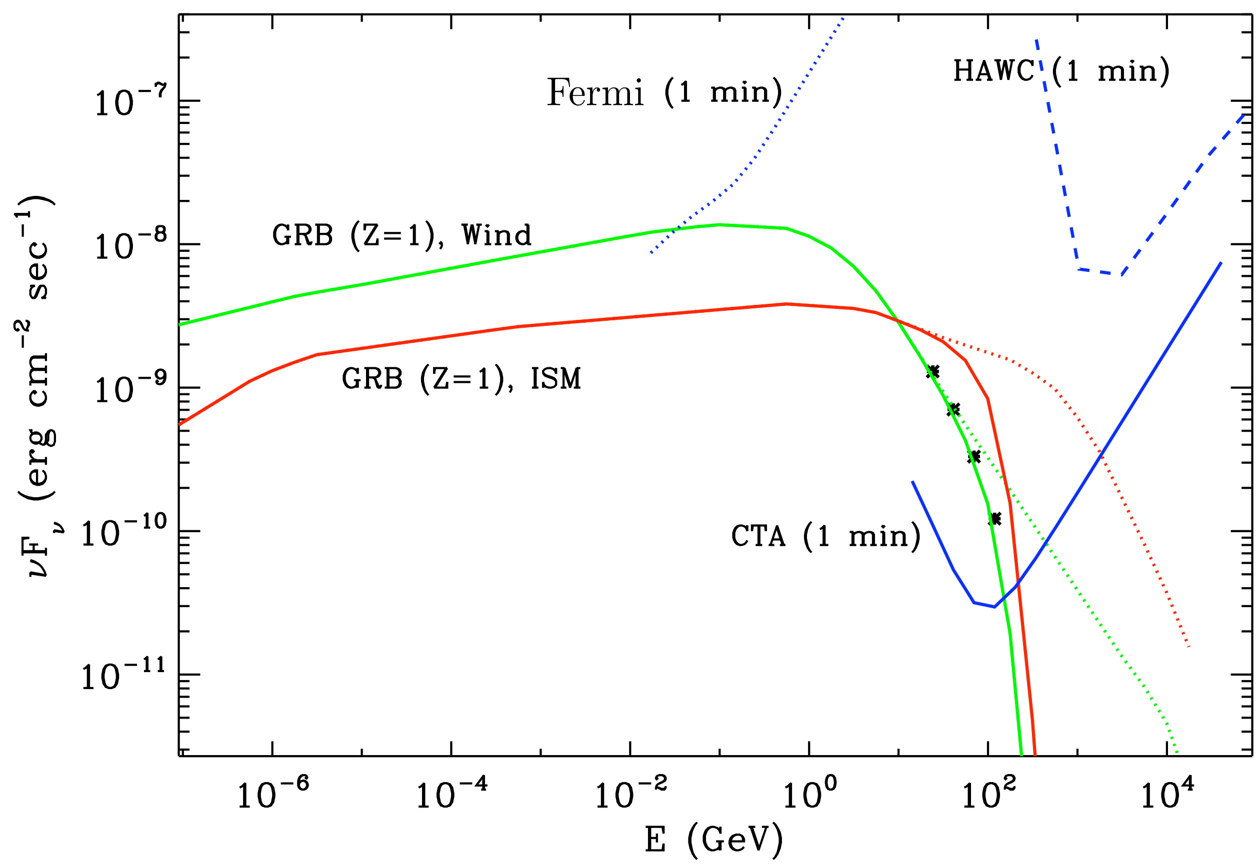
Simulated Sky Map with Improved Angular Resolution, FoV, Sensitivity   Digel, Funk and Hinton

Dark Matter



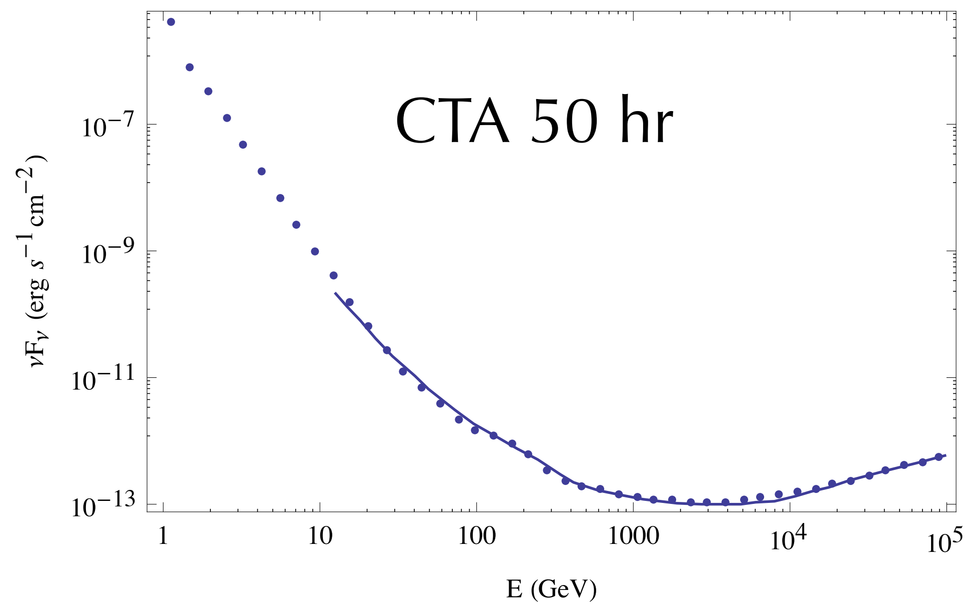
(JB 2011)

Gamma-Ray Bursts



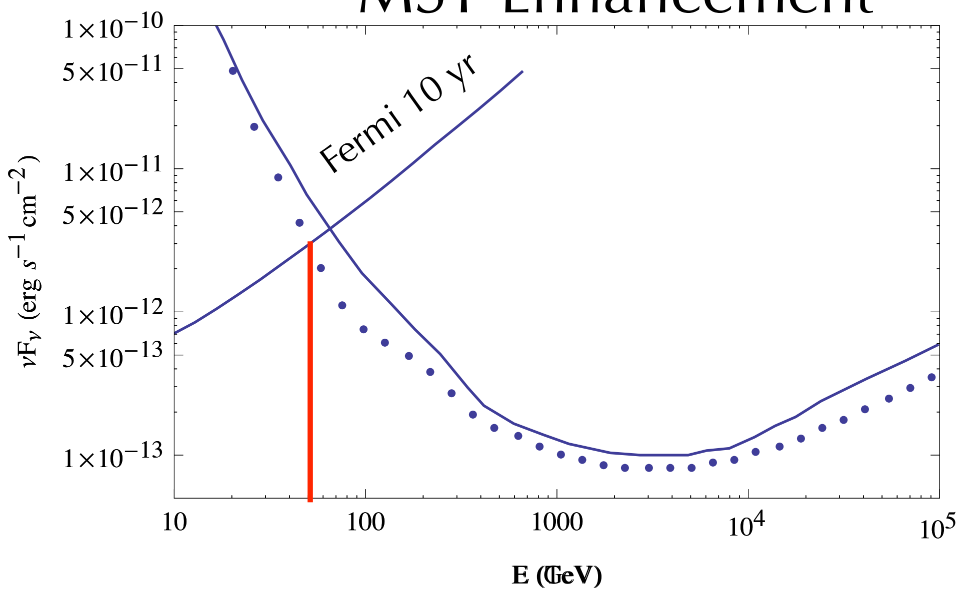
Answer to Dan's Question!

Yes - Energy threshold is important, but do we build more LSTs or MSTs?

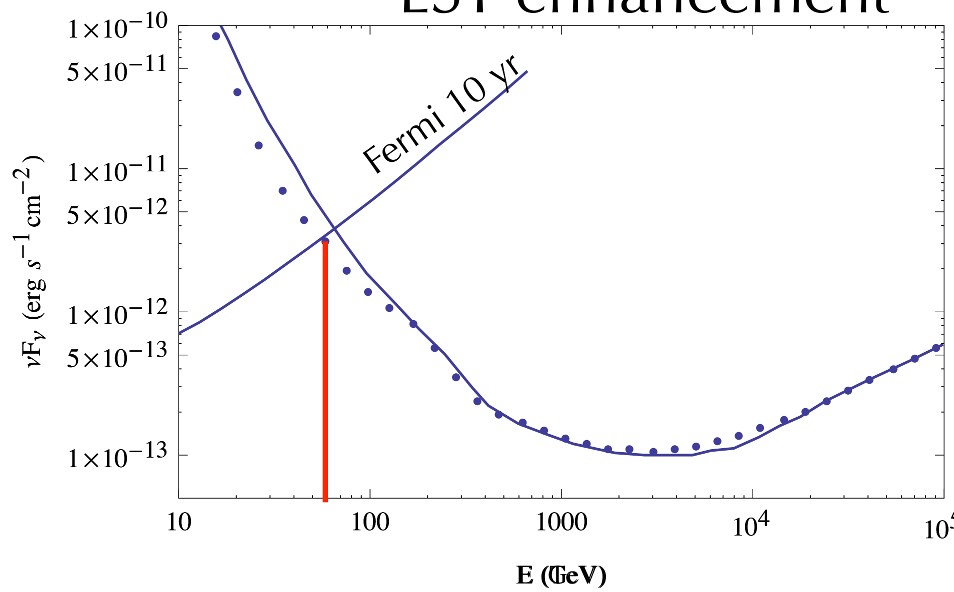


Text

MST Enhancement



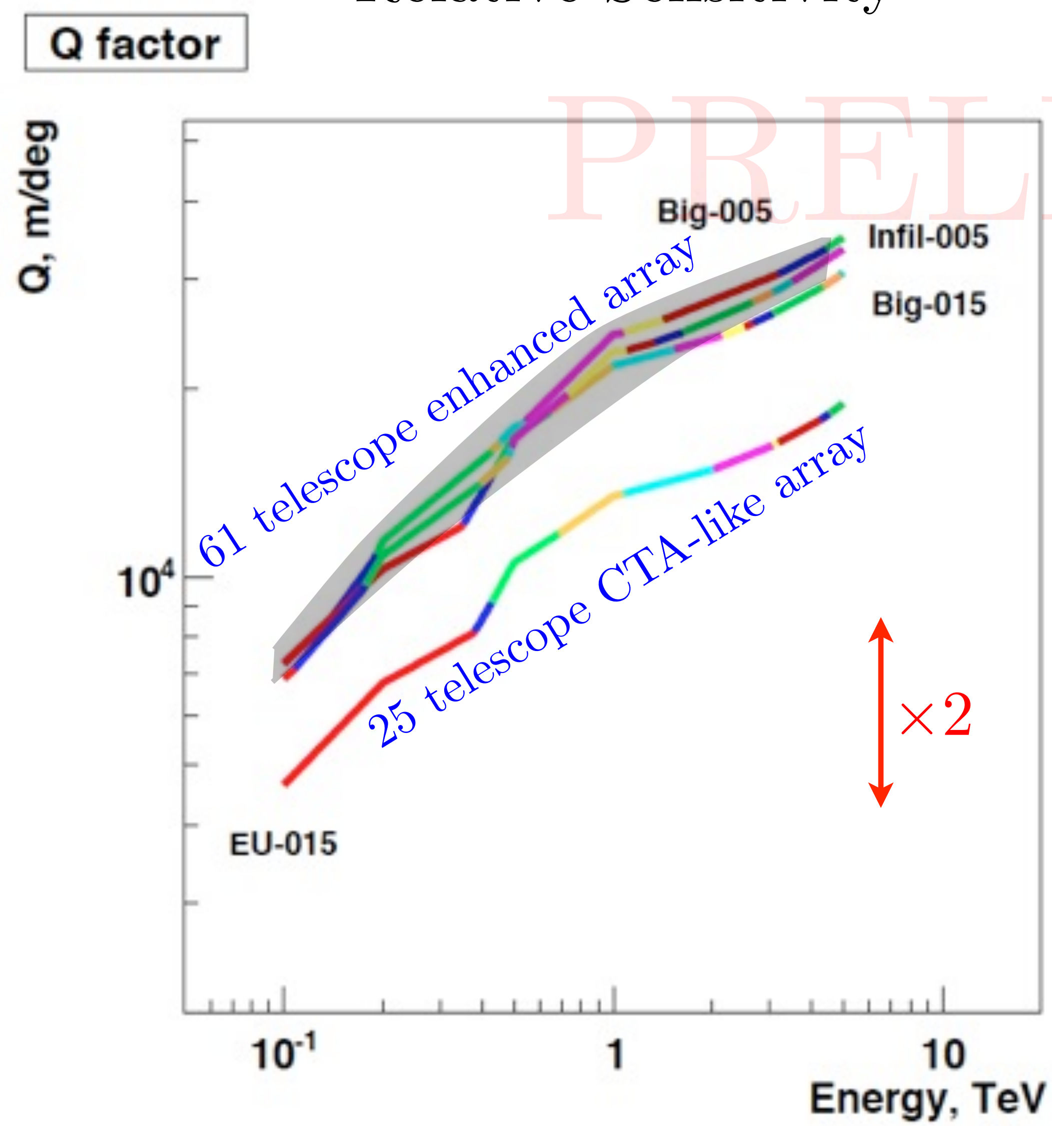
LST enhancement



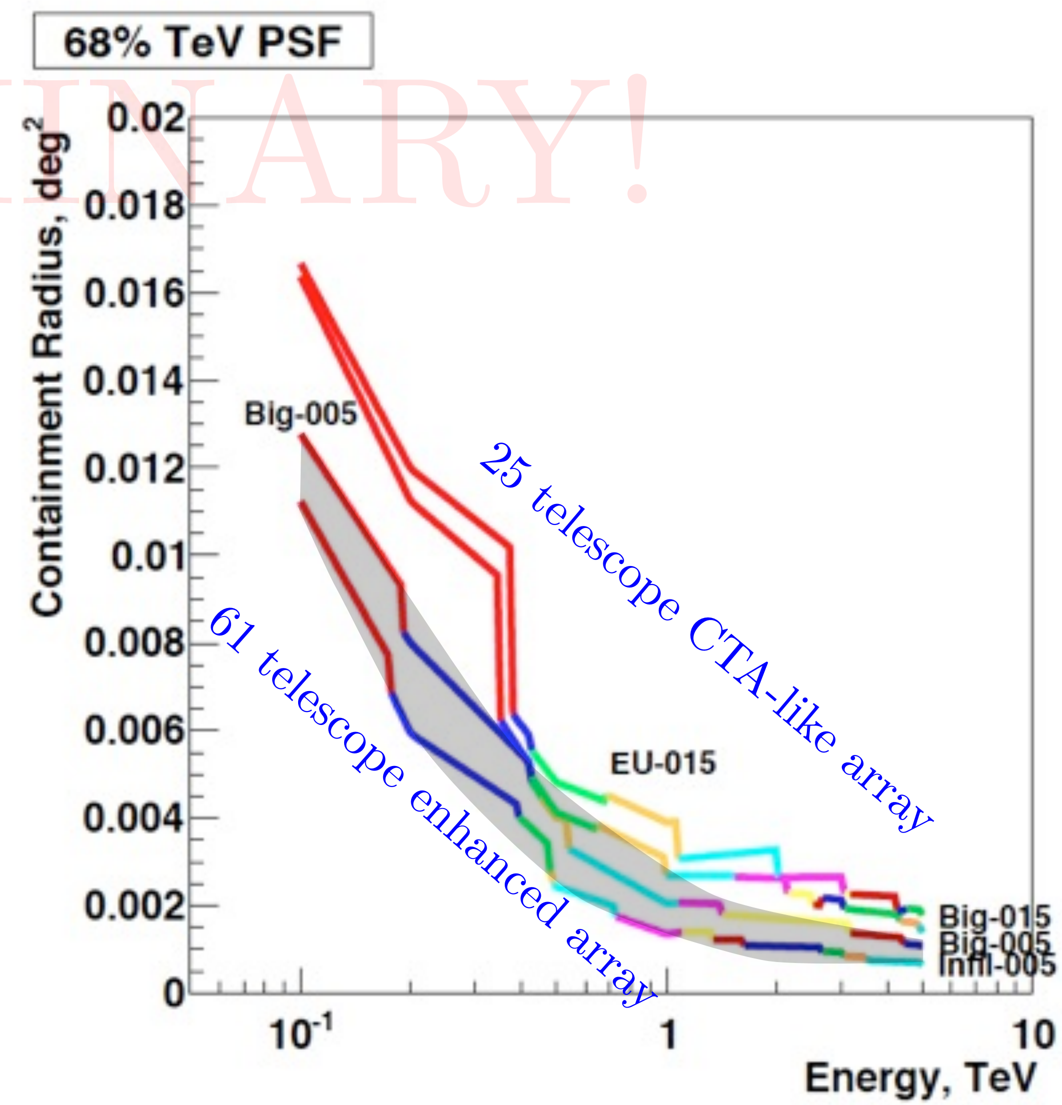
Equal cost enhancements - which do you choose?

CTA-US Enhancement

Relative Sensitivity



Angular Resolution



- With 36 additional U.S. telescopes, we expect improvements in both the sensitivity (left) and angular resolution (right) further improving DM sensitivity (preliminary results of simulation studies by Slava Bugaev for a CTA-like array of 25 telescopes or 61 telescopes)

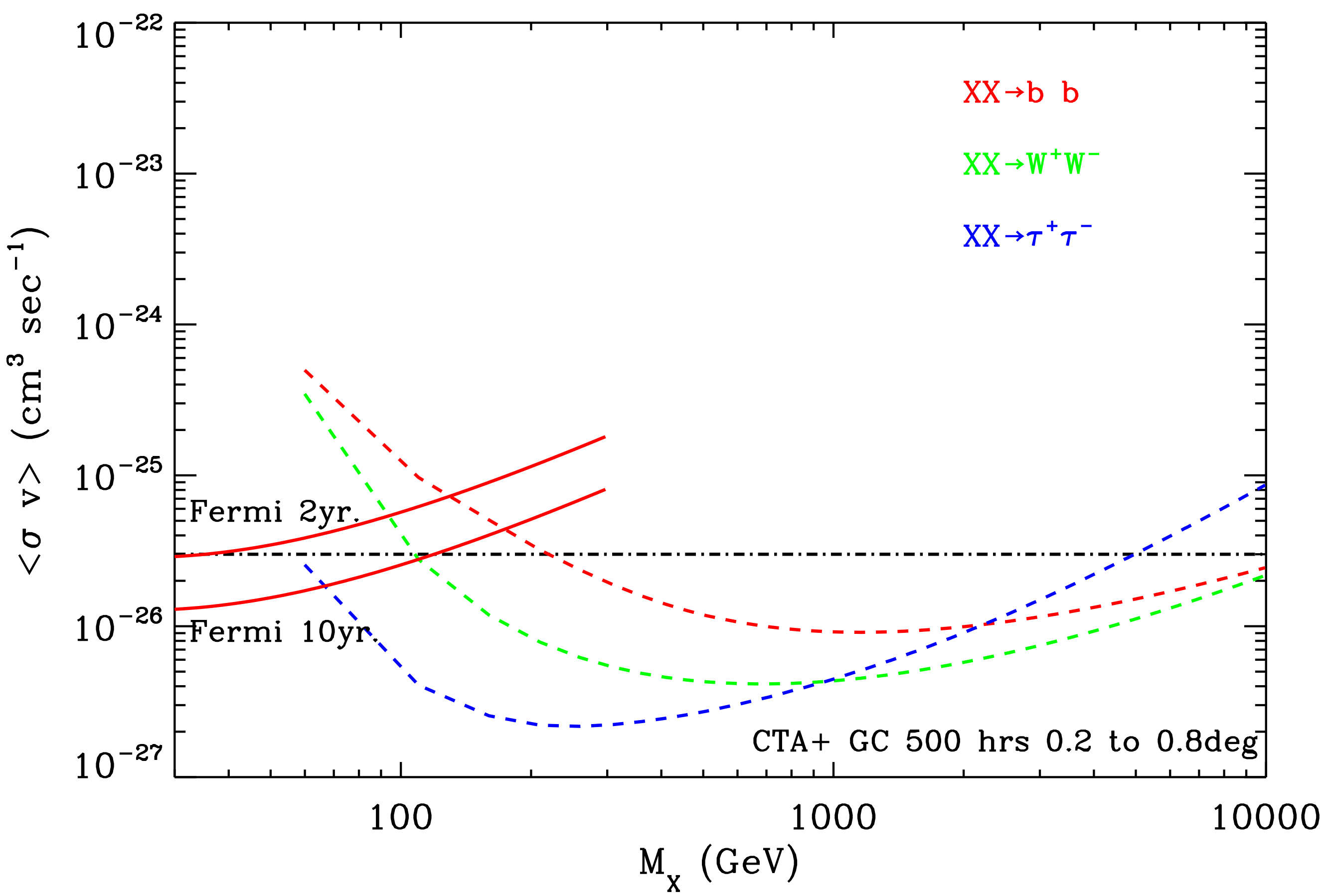
Calculation Details

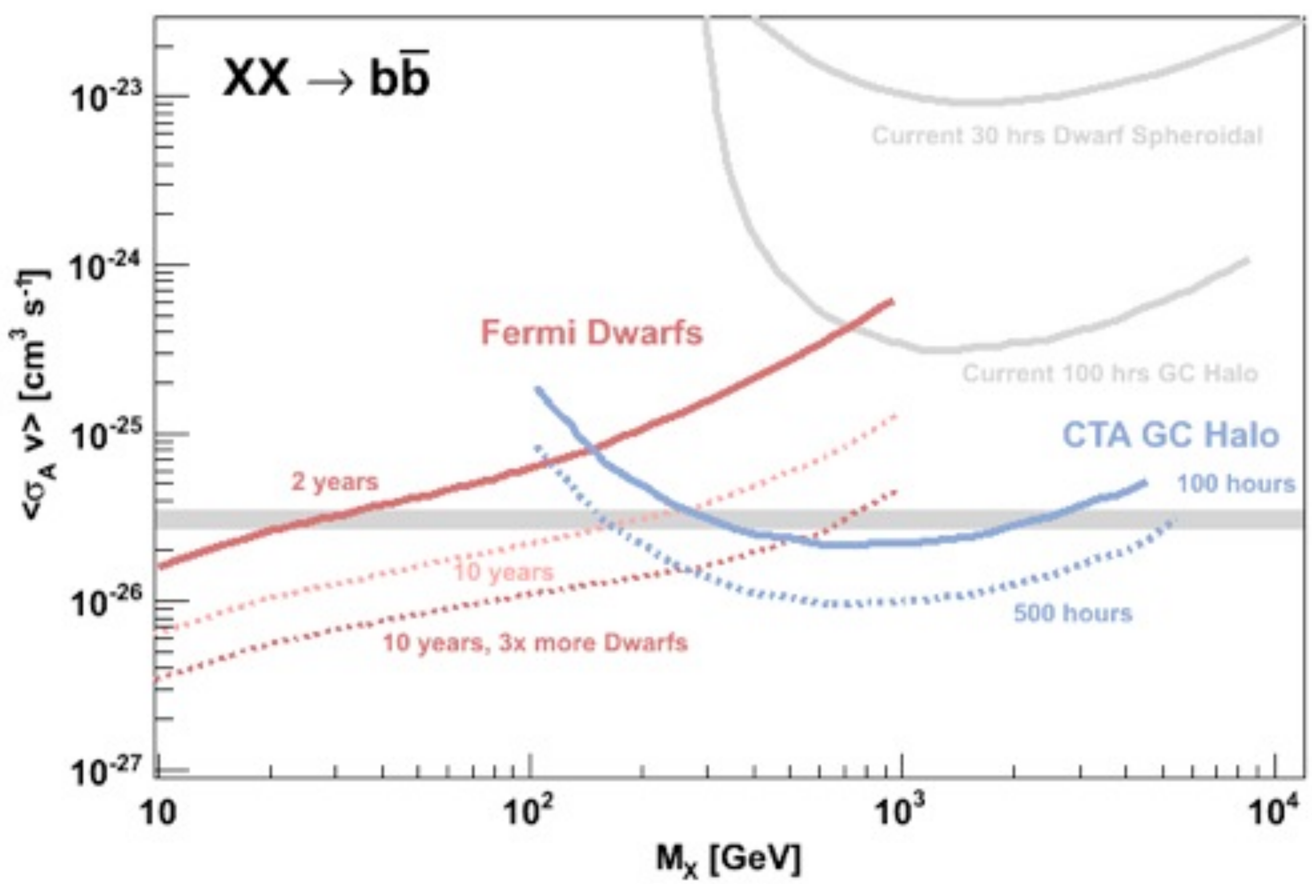
$$\text{Annihilation Signal} \sim \int_E d(\ln E) A_{\text{eff}}(E)\, t \left(E \frac{dN}{dE} * \text{energy resolution} \right) \int_{\Delta\Omega} d\Omega \left(\text{psf}(E) * \int_{\text{line of sight}} \rho^2 dl \right)$$

$$\text{Background} \sim \left[\int_E d(\ln E) A_{\text{eff}}(E)\, t \left(E \frac{dN_{\text{background}}}{dE} * \text{energy resolution} \right) \int_{\Delta\Omega} d\Omega \right]^{1/2}$$

- Include energy dependent PSF and spectrum in calculation of effective J-factor
- For sensitivity of an enhanced v CTA (with 36 additional U.S. telescopes,) I model sensitivity of baseline instrument using effective areas, and electron and cosmic ray backgrounds normalized to match "Configuration E" simulations in the CTA design study and scale area and angular resolutions.
- Fermi model uses published effective areas, angular resolution, and parameterizations of cosmic ray nuclei, electrons, diffuse galactic gammas, and extragalactic gamma-ray backgrounds. Electron and cosmic ray rejection are fit parameters to match differential sensitivity.
- Use parameterizations of Pythia results for continuum spectrum from various annihilation channels (courtesy Matthieu Vivier)

Other Estimates





- Comparison with estimate by Funk et al. (2012)

Optimizing SNR

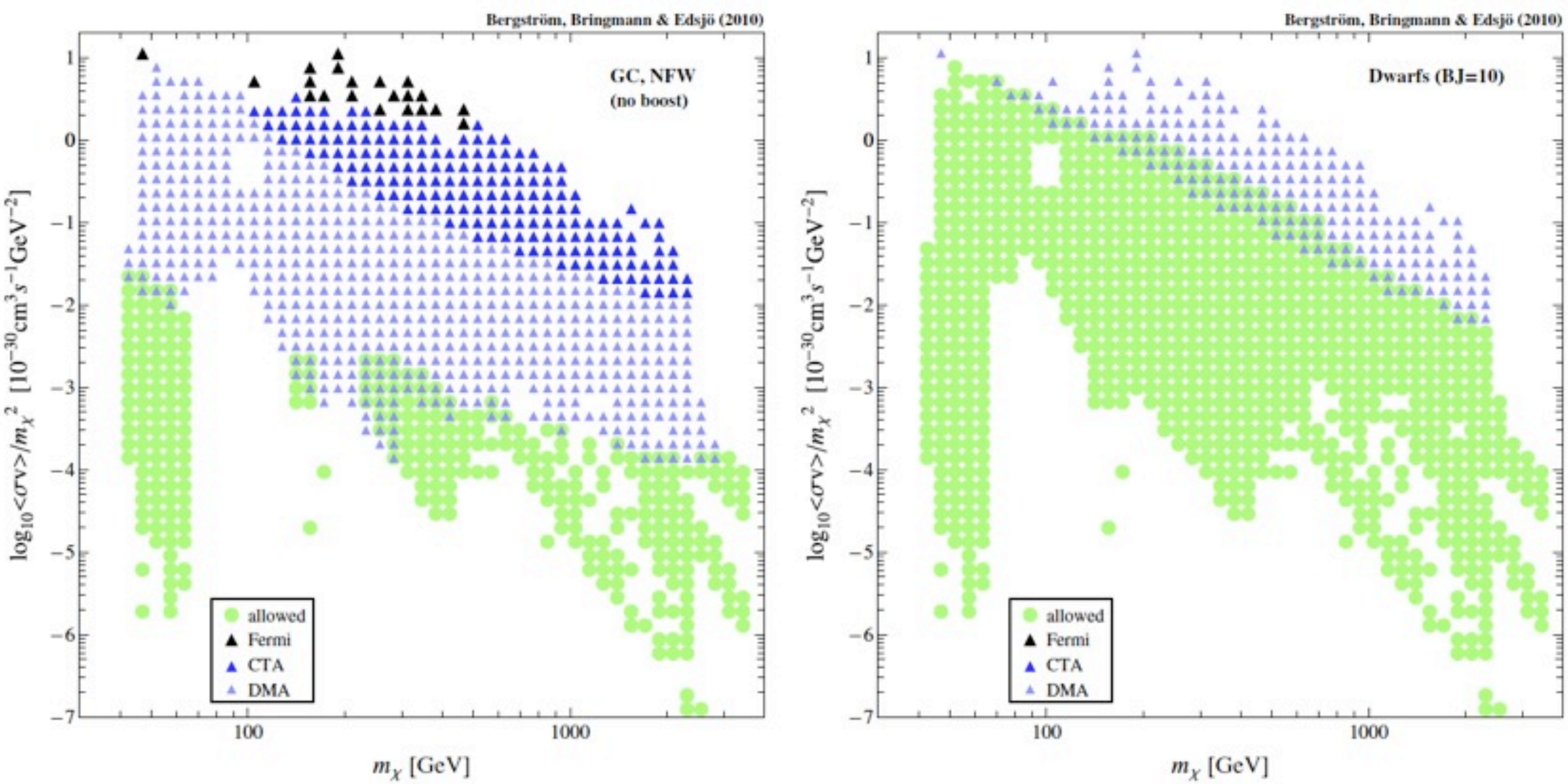
- Optimum angular aperture depends on energy dependent angular resolution, backgrounds, halo distribution, and significance of a point source at the center.

- For Sagittarius Dwarf with CTA optimum is 0.5deg at 200 GeV, 0.3deg at 1 TeV (used 0.5deg)

- For Fermi, optimum cut is 0.35 to 0.8 deg across the energy range (used 0.5deg)

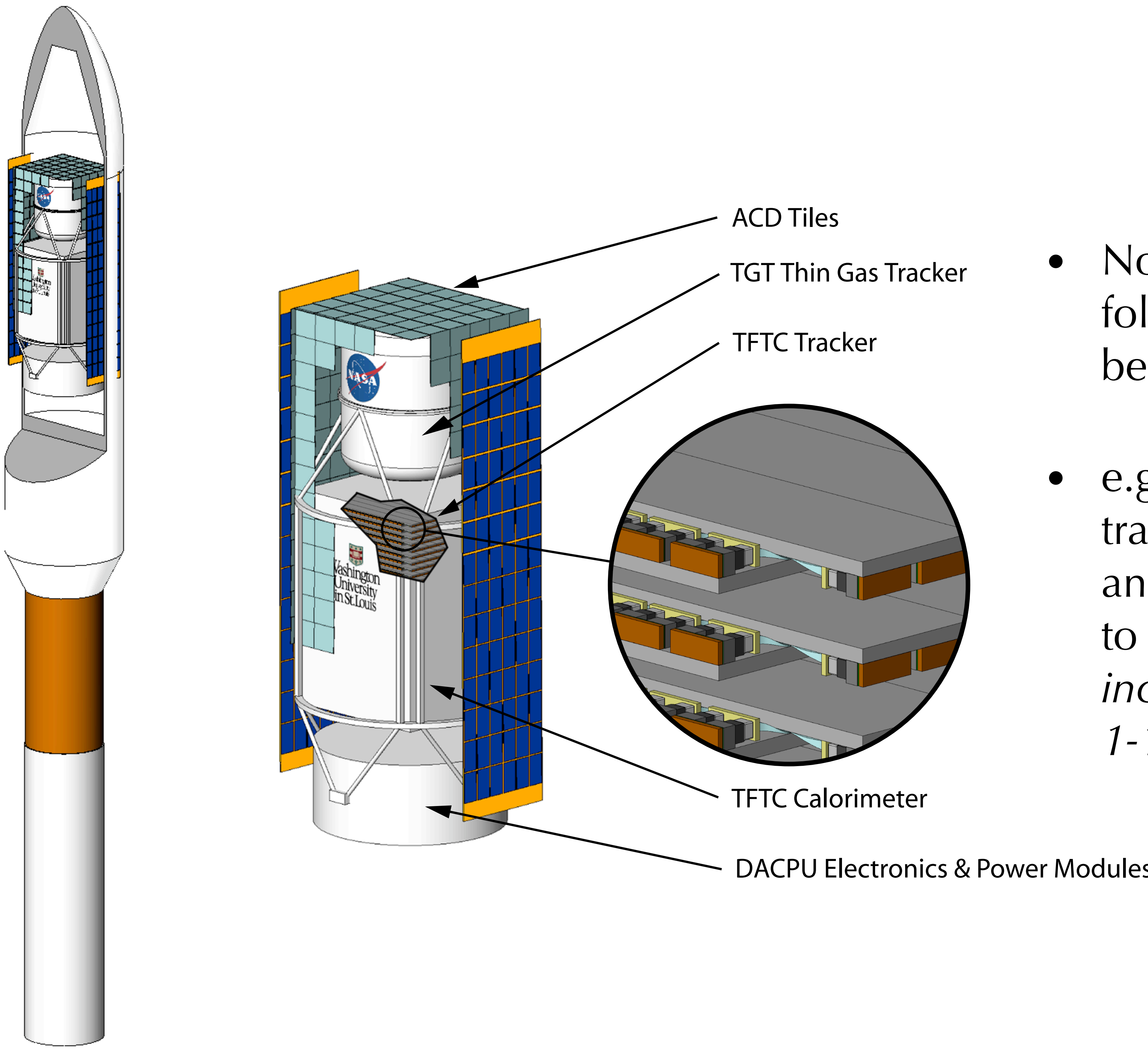
- For CTA observations of GC, optimum cut also depends on point source significance (ratio of signal to background), minimum radius depends on angular resolution (factor of 2 smaller with expanded CTA array) maximum radius up to 3deg is optimal, underscoring need for a wide field of view.

Other Estimates



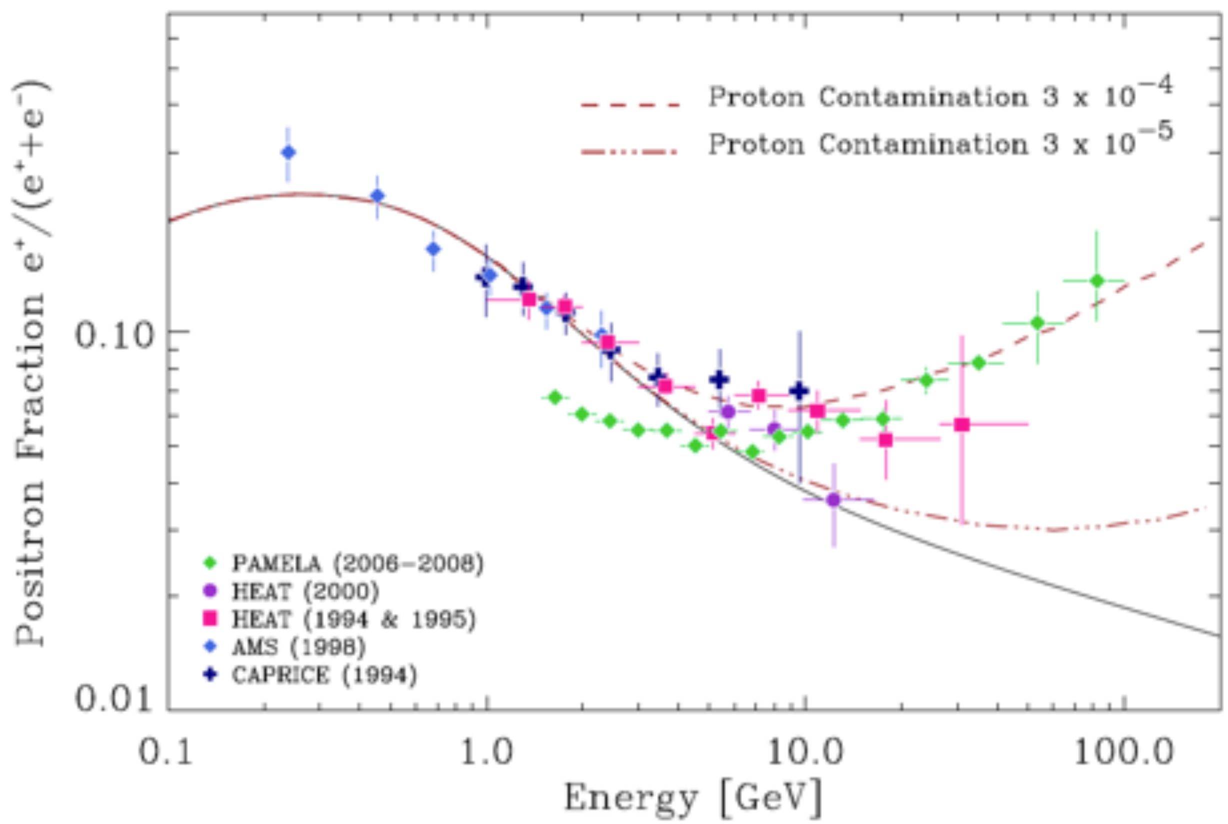
- Results consistent with estimated sensitivity of CTA and "DMA" in Bergstrom et al. (2011) calculated for GC with no boost (*LEFT*) and Dwarf Galaxy with modest boost (*RIGHT*)

Future Space Experiment?



- No serious proposals for a follow up to Fermi aimed at better DM sensitivity, but...
- e.g., APT concept using SF tracker, thin calorimeter and largest available shroud to get *order of magnitude increase in exposure in 1-10 GeV regime*.

Problems with Positrons



- Schubnell (2009; arXiv:0905.0444) points out that old measurements (pre 1990) showed rise in positron fraction - found to be a problem with instruments using small permanent magnets and limited particle ID.
- Intensity of CR protons exceeds that of positrons by a factor of $5x10^4$ above 10 GeV.
- PAMELA, originally designed to include a TRD, suffers from lack of strong particle discrimination.
- EC power is limited by the irreducible background from single pi^0 that mimic electromagnetic showers